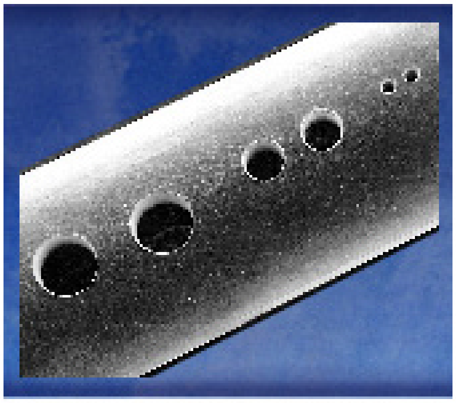
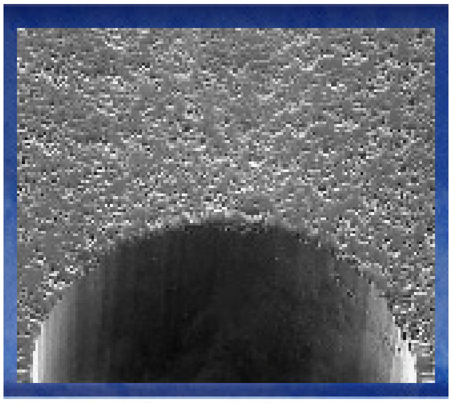
RESONETICS

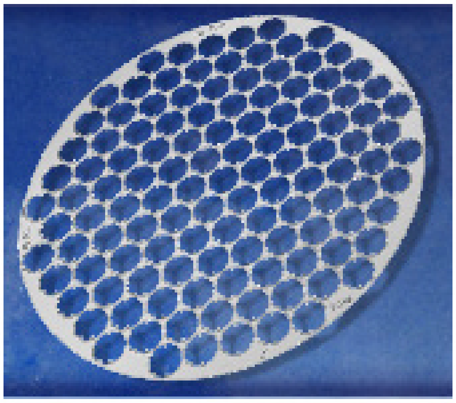
Laser Micromachining Seminar



EXCIMER LASER MACHINING



CO_2 LASER MACHINING



APPLICATIONS GUIDE

EXCIMER, CO_2, SOLID STATE,
LASER SYSTEMS

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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 shock or handling
2. **No solvent chemicals**
    - Reduced waste handling costs - environmentally clean
    - Lasers provide one-step alternative to chemical etching process
3. **Selective material removal**
    - proper selection of laser power on-target allows removal of one type of material without damage to the underlayers
    - Examples: skiving, wire stripping
4. **Flexibility**
    - Laser materials 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 Manufacturing**	**Electronics**	**Medical**	**General**
Profile cutting in sheet and plate metals	Profile cutting in plastics and wood	Via formation insulating material: Tab & MCM	Flow orifices <100 μm diameter	CVD diamond cutting
Seam and spot welding	Engraving	High accuracy wire stripping	Drilling and cutting delicate or thermally sensitive materials	Ceramic and glass micromachining
Cladding and drilling	Drilling	Skiving of flexible circuits	Micromachining applications where edge quality and cleanliness is critical	Thin film patterning; micro-lithography
		IC repair		

Table 1. Some typical laser applications.

Comparison of Available Machining Methods

	Practical Resolution Limit	**Attainable Aspect Ratio***	**Taper**	**Undesirable Side Effects**	**Status of Technology Development**
Excimer Laser	5 µm	>100:1	Yes	Recast Layer	Low
CO_2 Laser	200 µm	100:1	Yes	Recast Layer, Burring, Thermal	High
Nd:YAG	50 µm	100:1	Yes	Recast Layer, Burring, Thermal	High
EDM	100 µm	20:1	No	Surface Finish	Moderate
Chemical Etch	250 µm	1:1.5	Yes	Undercutting	Moderate
Mechanical	Ø 100 µm	10:1	No	Burring	Moderate

*Depth:Hole size

Table 2. Comparison of available machining methods and their characteristics.

Laser Theory and Operation

- Brief Review of Laser Physics
- Types of Lasers and Their Applications
- CO_2 Lasers
- Solid State Nd^{+3} Lasers
- Excimer Lasers

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

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

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

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

$$\lambda = c/\nu,$$

where c = speed of light = 3×10^8 m/s.

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

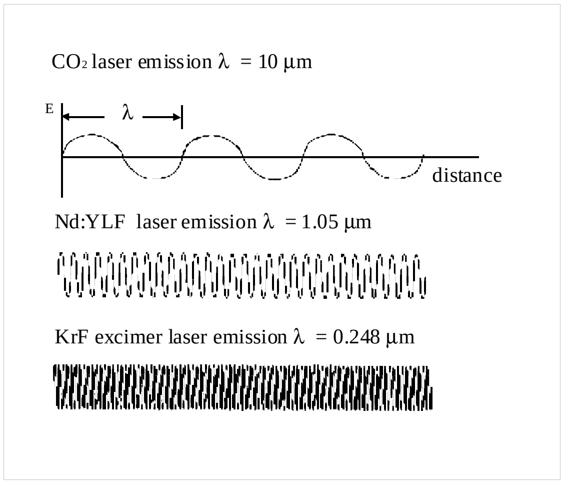
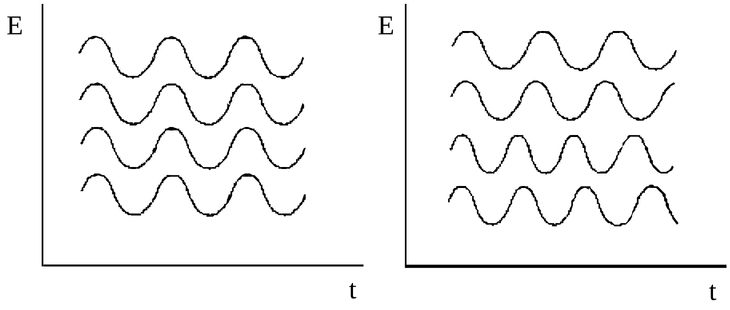


Figure 1. Physical description of wavelength.

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.



(a) Coherent light (b) Non-coherent light

Figure 2. Coherent vs. non-coherent 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. In machining applications, divergence is undesirable because it leads to reduced energy and distorted images at the target surface.

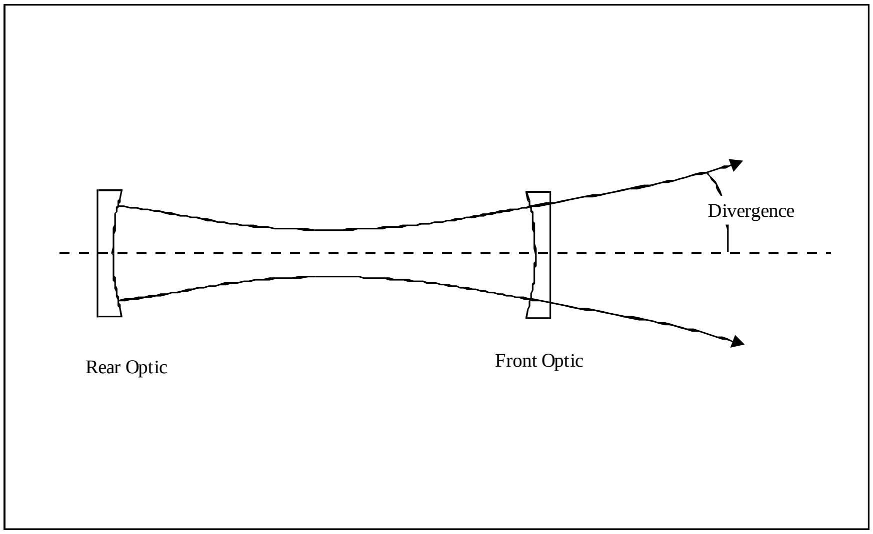


Figure 3. Divergence of a laser beam. Divergence is normally specified in milliradians.

Photon Interactions with Matter

Possible photon interactions with matter include the following:

- photon absorption - the photon is absorbed by an atom or molecule
- photon 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

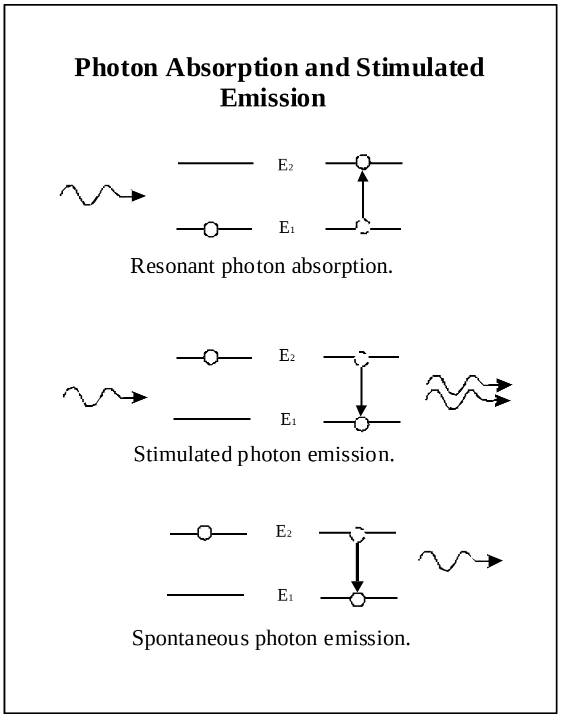


Figure 4. Energy, wavelength, phase and direction of a stimulated photon is exactly same as the incident photon.

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 a continuous or even a pulsed output. A population inversion exists between two lasing energy states when there are more species occupying the upper state than the lower. The process used to excite lower energy atoms or molecules to their excited states is called “pumping”.

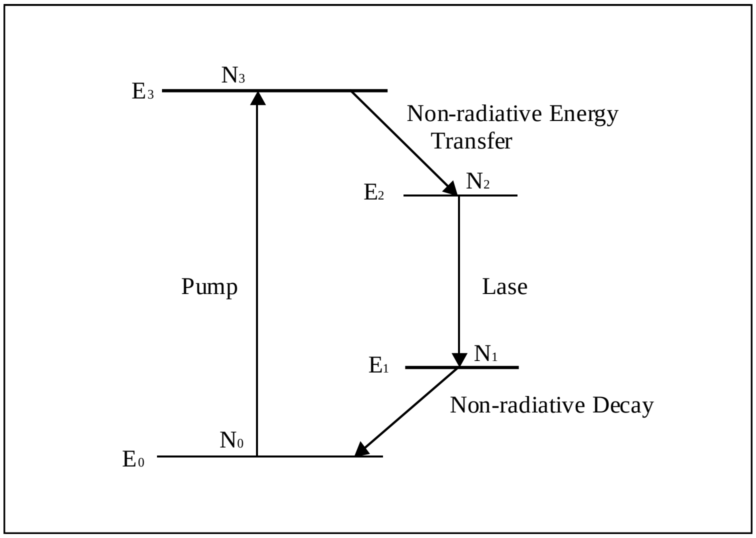


Figure 5. Population inversion in a 4-level system exists when the number of species or individuals N_2 is greater than N_1.

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 the figure above. Consequently, the laser pumping mechanism must be sufficient in counteracting 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 $\mathbf{t}_1$ or $\mathbf{t}_2$ are too lengthy, insufficient species in the upper energy state will exist to 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. The lasing medium can be a gas, solid, liquid, or in the case of semiconductor lasers, electrons. The pump process excites the atoms or molecules of the lasing medium to their upper energy states 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 a portion of the photons back and forth through the laser medium for increased amplification.

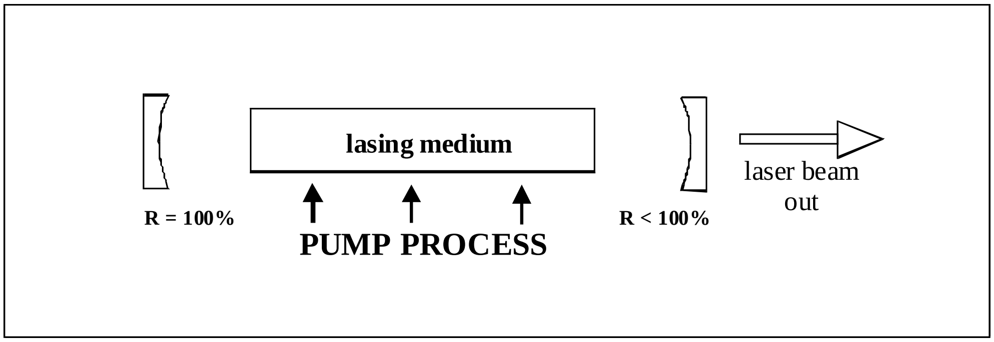


Figure 6. Elements of a laser.

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 near 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 collision excitation

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

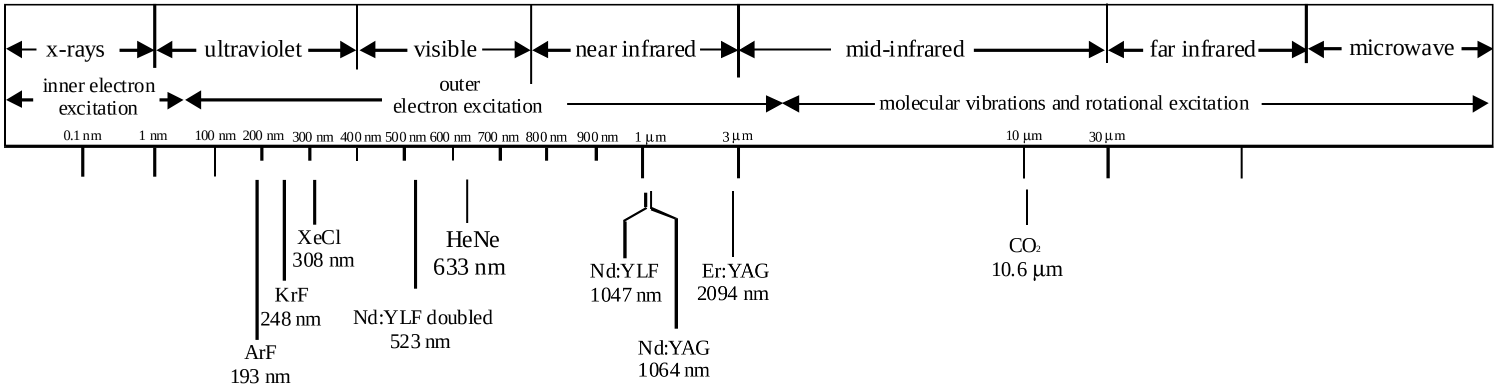


Figure 7. Laser categorization according to wavelength in the electromagnetic spectrum.

Lasers are categorized according to lasing medium. The four basic types of laser media are: gas, solid state, semiconductor and liquid dye. Only gas and solid state lasers are practical for most industrial machining applications.

Type	**Medium**	**Wavelength**
Gas Lasers	Excimer	193-351 nm
	CO_2	10 μm
Solid State Lasers	Nd:YAG	1.064 μm
	Nd:YLF	1.047 μm

Table 3. Common lasers used in industry. Note that none of these emissions are in the visible light spectrum.

CO_2 Lasers

Characteristics of Carbon Dioxide Lasers

- most common laser in industry
- inexpensive
- wide range of power output capabilities
- high efficiency
- oscillating frequency is 9.4-11.0 µm (infrared)
- long penetration depth (5 - 10 µm or more)
- machining is a thermal process - the beam performs its cutting and drilling functions by overloading the target surface thermally
- 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 as 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 gas discharge.

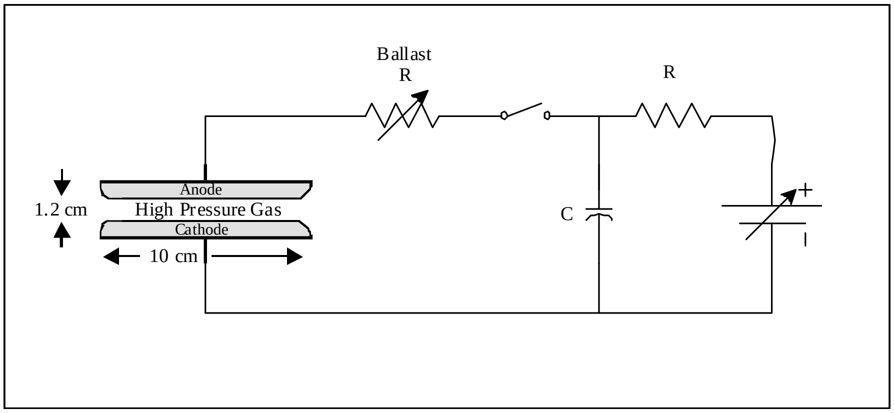


Figure 8. Simplified electric discharge circuit for a typical TEA laser.

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 the 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

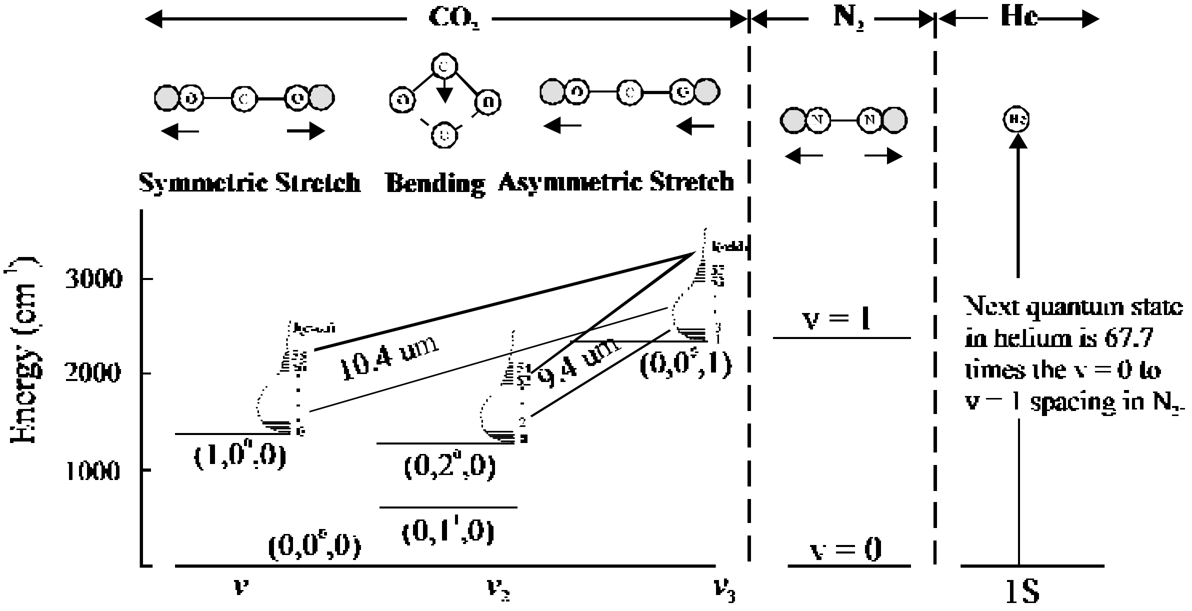


Figure 9. CO_2 laser pumping scheme and energy-level diagram. The quantum numbers ($n_1n_2n_3$) indicate the amount of energy in each of the vibrational energy modes illustrated at the top. The J quantum numbers indicate rotational energy states. The vertical axis is graduated in cm^{-1} which is another measurement of energy equivalent to 1/l.

Energy Transfer

Excited CO_2(001) molecules are formed by three methods:

- 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 is mixture of CO_2:N_2:He)
    1. Electrons in the gas discharge current excite N_2 molecules vibrationally by inelastic collision

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

    2. Excited N_2^* molecules transfer energy to CO_2 molecules

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

- 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.

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

Table 4. Types of CO_2 lasers.

Increased CO_2 laser output power can be achieved either by increasing the volume of the cavity or the gas pressure. Unfortunately, these measures also increase heat generated inside the cavity until lasing can no longer be sustained. The Lumonics IMPACT and Lasertechnics Blazer 6000 both employ a slow gas purge and water cooling system to alleviate this problem. The IMPACT and Blazer 6000 are used for machining at Resonetics or are installed in materials processing systems for customers. These lasers are called TEA (transverse excitation atmospheric) lasers because the electrodes are constructed along the axis of the resonator cavity.

Laser Parameter	Lumonics IMPACT	Blazer 6000
Max pulse energy	500 mJ	5 Joules
Max average power	75 Watts	60 Watts
Wavelength	10.6 μm	10.6 μm
Pulse repetition rates	0-150 pulses per second	0-15 pulses per second
Beam cross-section	12 x 12 mm	1.15 x 0.75 inch

Table 5. Parameters for two medium powered industrial CO_2 TEA lasers.

Two examples of two other medium power CO_2 lasers in use at Resonetics are the Coherent Diamond 64 and the Synrad Series Duo-Lase Series 48-5 CO_2 Laser. These lasers are hermetically sealed and require no gas purge. Instead, the lasers are restricted in power output and have a finite gas lifetime. Both the Diamond 64 and Duo-Lase units employ radio frequency (RF) excitation in place of the normal electrical excitation impressed across the electrodes. The advantages of RF discharge excitation are lower operating voltages and higher pulse repetition rate capability. Both lasers are water cooled.

Laser Parameter	Diamond 64	Synrad Duo-Lase 48-5
Max pulse energy	350 mJ	500 mJ
Max average power	150 Watt	50 Watts
Wavelength	10.6 μm	10.6 μm
Pulse repetition rates	10,000 pulses per second	50-400 pulses per second
Beam cross-section	7 mm diameter	3.5 mm diameter

Table 6. Two medium power, sealed, RF-discharge CO_2 lasers.

The Coherent Diamond 64 utilizes a new laser technology designated "slab-discharge". The electrodes in a slab-discharge design are two parallel plates that hold the gas plasma in a trapezoidal-shaped region between the plates. The beam traces a zigzag path between the plates. An additional feature on the Diamond 64 laser is an improved square-wave RF discharge pulse that packages more energy into a single laser pulse. According to Coherent, the improved design features of the Diamond 64 result in the following beam characteristics:

- small spot size
- high peak power
- square-wave pulse shape
- high pulse repetition rate

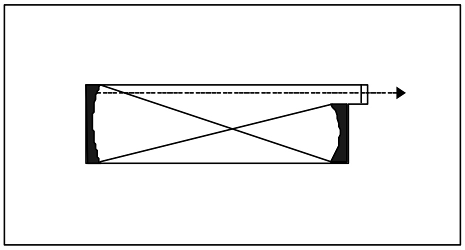


Figure 10. Diamond laser cavity design.

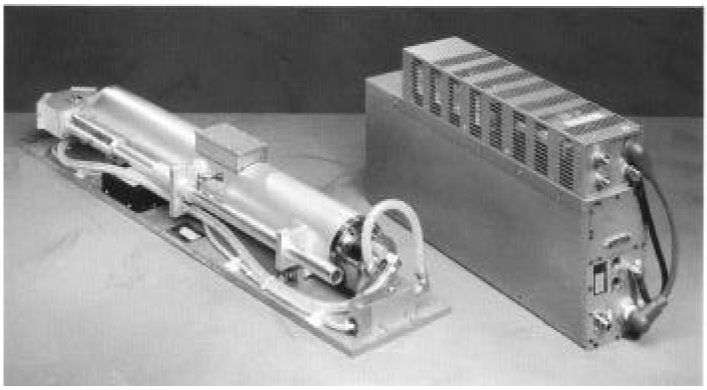


Figure 11. Diamond 64 laser system components.

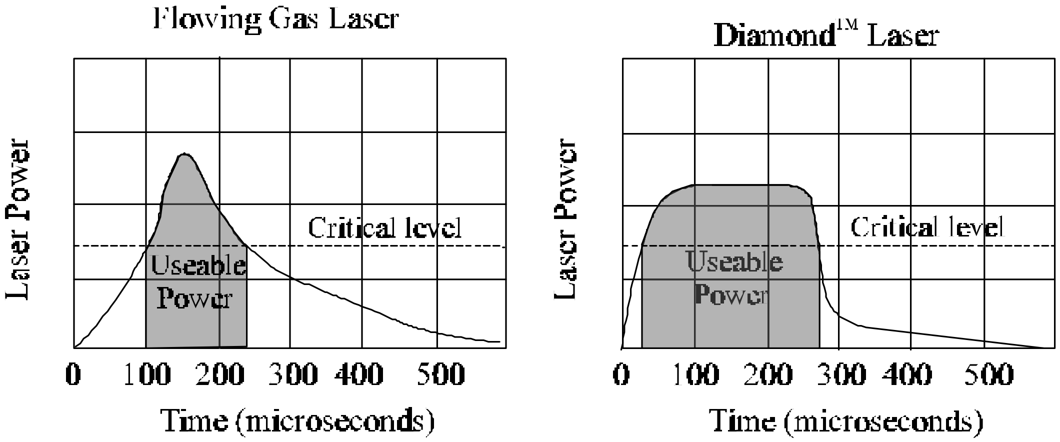


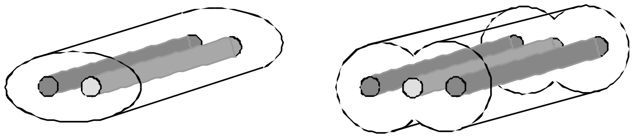
Figure 12. The Diamond^{TM} Laser produces a square pulse with more energy per pulse than most CO_2 lasers of its size.

Important CO_2 Machining Characteristics

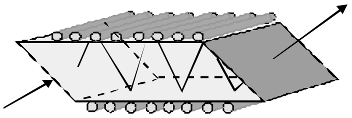
- Material interaction via thermal overload and vaporization
- Penetration depth is 5 to 10 μm
- Ultimate feature resolution ~10 μm
- Practical feature resolution ~50 μm
- Inert gas used to limit oxidation in process area

Solid State Nd^{3+} Lasers

Most 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 $Y_3A_{l5}O_{12}$ (YAG), $LiYF_4$ (YLF) and amorphous glass. The Nd:YAG and Nd:YLF lasers are discussed because they are the most common solid state lasers in industry.



(a) single flashlamp (b) double flashlamp



(c) multi-flashlamp with complete internal reflection

Figure 13. Typical solid state configurations.

Characteristics of Nd Lasers

- **Typical solid state lasers are pumped optically by arc lamps or flashlamps. Arc lamps typically are used for continuous wave (cw) pumping; flashlamps are used with pulsed lasers.**
- **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.**

- **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**

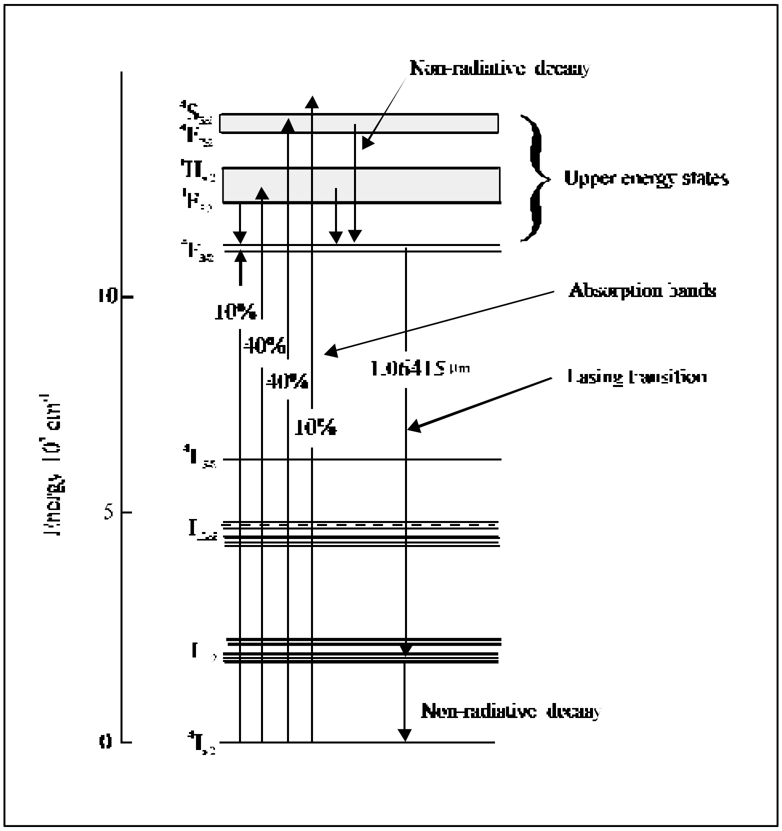


Figure 14. Energy-level diagram and pump scheme for the Nd:YAG laser.

Characteristics of Nd:YAG/YLF 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 7. Characteristics and applications of Nd:YAG/YLF 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 to the environment. The combined loss of photons traveling 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. The Q switch device is an electronic shutter, sometimes called a Pockels cell, that is triggered open and shut by an electrical signal.

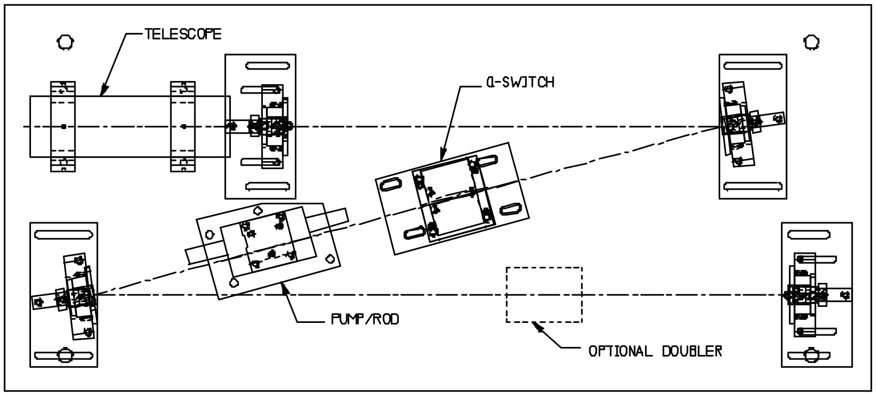


Figure 15. Optical layout for an Nd:YLF laser showing Pockels cell Q switch device.

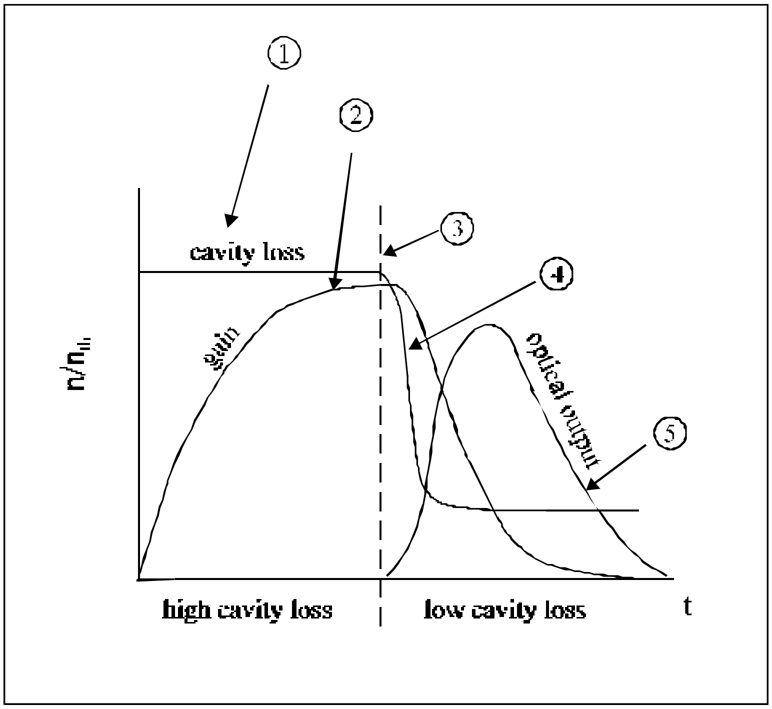


Figure 16. Q switch technique, step by step.

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
6. Sequence is repeated for each laser pulse

Nd:YLF vs. Nd:YAG

- The Nd:YLF and Nd:YAG are not identical in laser characteristics:

- Nd:YAG wavelength is 1.064 µm, Nd:YLF 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, $\mathbf{t}_{\mathrm{YLF}}$,is about three times longer than $\mathbf{t}_{\mathrm{YAG}}$.

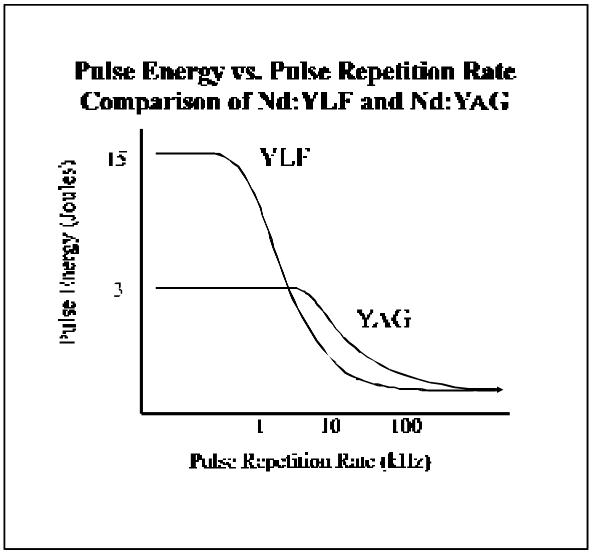


Figure 17. Energy comparison of Nd:YLF vs. Nd:YAG.

- 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 thermal lensing phenomenon that focuses the beam just outside the laser rod.

- YLF host lasers are relatively new technology and are still undergoing research

Harmonic Generation

Following the proliferation of laser experimentation in the 1960s, 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 nuclei in these materials oscillate in response to incident radiation such that two separate wavelength emission exit the material. The output of these emissions include the original frequency and a component half the wavelength of the incident beam. This phenomenon is called harmonic generation.

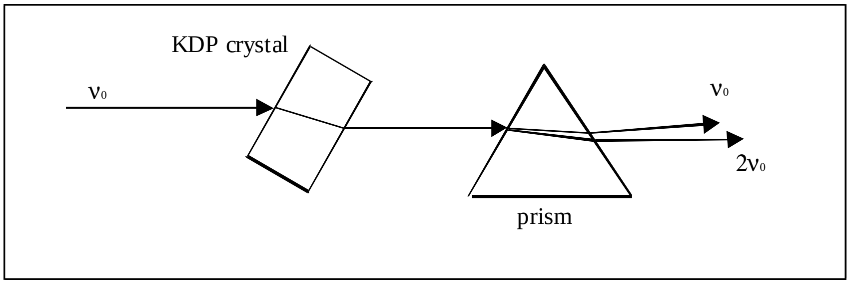


Figure 18. Harmonic generation of a laser beam through an anisotropic medium.

Harmonic generation is useful in creating different wavelengths, however, total output energy of the shorter wavelenght 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 8. Harmonic generation frequencies of Nd:YAG and Nd:YLF laser emissions.

Excimer Lasers

- Brief History of the Excimer Laser
- Excimer Laser Transition and Pump Scheme
- Major Components of an Excimer Laser
- Beam Profiles
- Typical Examples of Excimer Lasers
- Operation and Maintenance Costs

Brief History Of The Excimer Laser

- **Late 1970's- Lasing first demonstrated**
- **Early 1980's- First commercial devices appear (Lambda Physik EMG series)**
    - 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)**
    - 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 installations (IBM, Siemens)
- **Late 1980's - More engineering advances - "Industrialized" lasers appear (LPXi series)**
    - 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)
    - 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

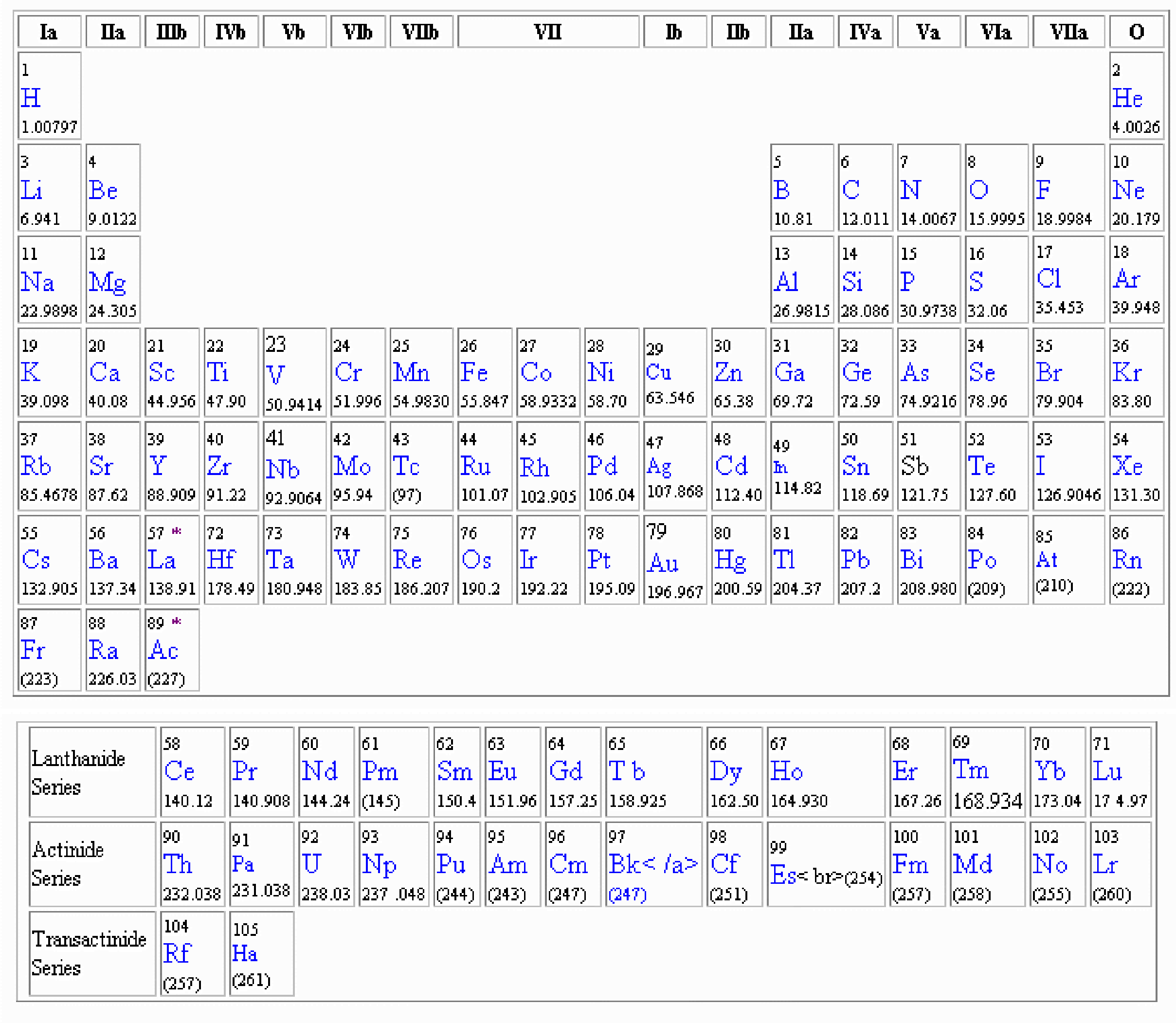
- Excimer lasers become known as the “third” industrial laser alongside CO_2 and solid state lasers

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. Each gas mixture has its own spectroscopy and pump scheme.

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	Low power, short gas life, not very useful
KrF	248 nm	10^7 pulses	50-100 Watts	Good industrial wavelength and power
XeCl	308 nm	2 x 10^7	50-150 Watts	Good industrial wavelength, particularly on glass products
XeF	351 nm	10^6	< 50 Watts	Not absorbed by some materials

Table 9. 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. Such a compound is called a "dimer" molecule and can be used as the active medium in an excimer laser.



Ia	IIa	IIIb	IVb	Vb	VIb	VIIb	VII			Ib	IIb	IIa	IVa	Va	VIa	VIIa	O
1 H 1.00797																	2 He 4.0026
3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.0067	8 O 15.9995	9 F 18.9984	10 Ne 20.179
11 Na 22.9898	12 Mg 24.305											13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.06	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.9414	24 Cr 51.996	25 Mn 54.9830	26 Fe 55.847	27 Co 58.9332	28 Ni 58.70	29 Cu 63.546	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.909	40 Zr 91.22	41 Nb 92.9064	42 Mo 95.94	43 Tc (97)	44 Ru 101.07	45 Rh 102.905	46 Pd 106.04	47 Ag 107.868	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.9046	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	57 * La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.980	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.03	89 * Ac (227)															

Lanthanide Series	58 Ce 140.12	59 Pr 140.908	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 T b 158.925	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 17 4.97
Actinide Series	90 Th 232.038	91 Pa 231.038	92 U 238.03	93 Np 237 .048	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk< /a> (247)	98 Cf (251)	99 Es< br>(254)	100 Fm (257)	101 Md (258)	102 No (255)	103 Lr (260)
Transactinide Series	104 Rf (257)	105 Ha (261)												

Figure 19. Periodic table of the elements showing the rare gas elements on the far right.

Excimer Laser Transition and Pump Scheme

The pump scheme for the KrF excimer laser shown below 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 from 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.

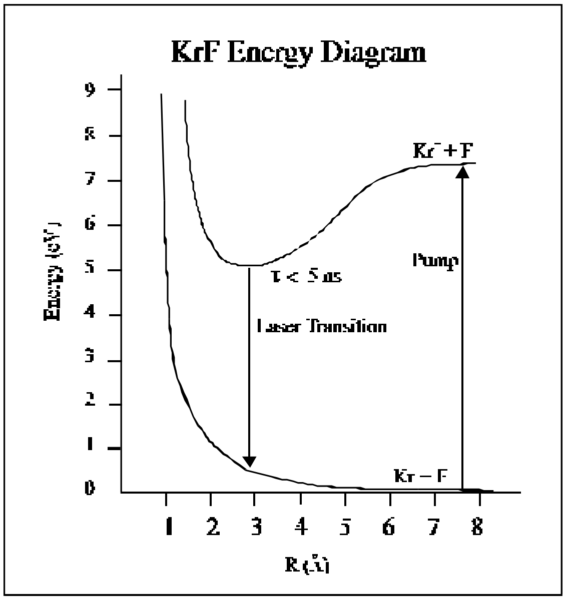


Figure 20. Energy diagram and pump schematic for KrF excimer laser. The vertical axis is graduated in electron volts (1 eV = 1.6 x 10^{-19} Joule). The horizontal axis is nuclear separation, graduated in angstroms (1 angstrom = 10^{-10} meters).

Important Properties of KrF and Other Excimer Lasers

- Since the atoms undergoing decay to the ground state are repelled, photon absorption to the upper state is non-existent. This condition and the high stimulated emission cross-section for KrF makes a population inversion easy to establish and the laser medium gain very high.

- The frequency of the excimer uv emission is sufficiently energetic to break the chemical bonds of most materials. Machining is accomplished through ablation instead of thermal overload.

- The pumping mechanism for excimer lasers is a gas discharge with 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 in proper 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. The voltages and currents required for excimer laser operation test the limits of electronic technology. Consequently, excimer lasers are more complex than other types of lasers, require more maintenance and are more expensive to maintain.

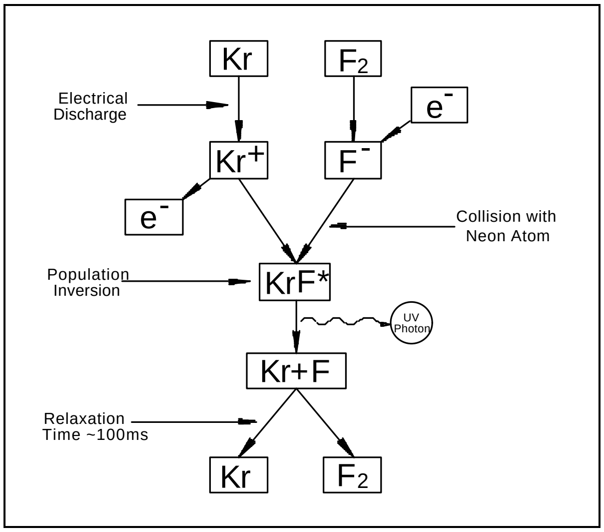


Figure 21. Simplified diagram of molecular transition in the KrF excimer laser.

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.

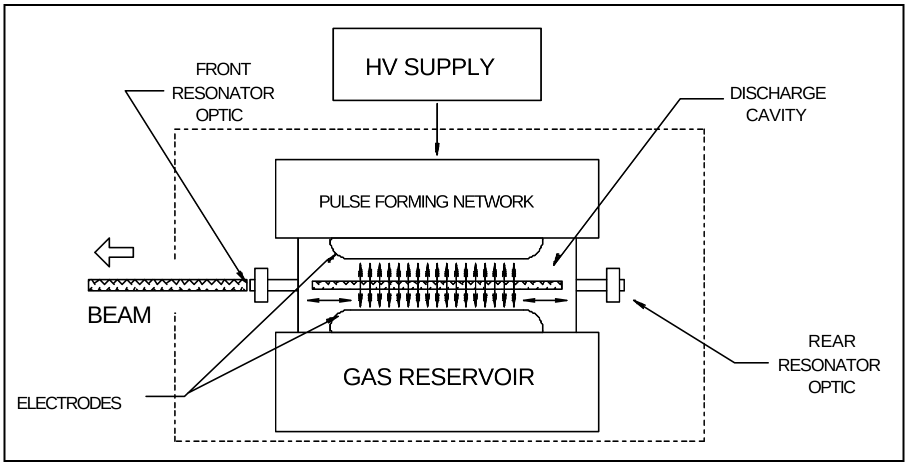


Figure 22. Basic components of the excimer laser.

Pulse Forming Network

The purpose of the discharge circuit in an excimer laser is to deliver an excitation pulse of up to 45 kv to the electrodes and preionization pins.

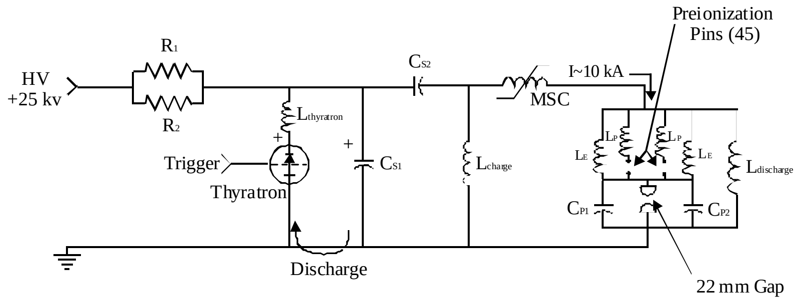


Figure 23. Electrical schematic of a typical discharge module in an excimer laser.

Operation of the Discharge Circuit

1. Initially the thyratron switch is open, storage capacitor banks C_{S1} and C_{S2} are charged and there is no current through the magnetic switch (MSC) and electrodes.

2. The thyratron switch is triggered closed, causing C_{S1} to discharge. The voltage across the thyratron electrodes is reversed and a trickle current begins to flow in the magnetic switch.

3. The initial inductance L_{MSC} is high, relative to L_{charge},. As the trickle current increases, the MSC saturates so that L_{MSC} is reduced to a point where full current discharge from C_{S1} and C_{S2} flows to the preionization pins and electrodes.

4. If C_{S1} and C_{S2} are equal, the voltage across the MSC and electrodes is effectively doubled such that approximately 45 kv is impressed across the electrodes.

5. Resistors R_1 and R_2 limit the current flow in the circuit.

6. $L_{thyratron}$ reduces wear on the thyratron by permitting switching operation at risetimes well within its capacity.

7. Inductors L_P and L_E control the preionization timing, relative to electrode excitation.

8. Peaking capacitors C_{P1} and C_{P2} control the shape and length of the excitation pulse.

9. Inductor $L_{discharge}$ relaxes the circuit after the thyratron opens.

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.

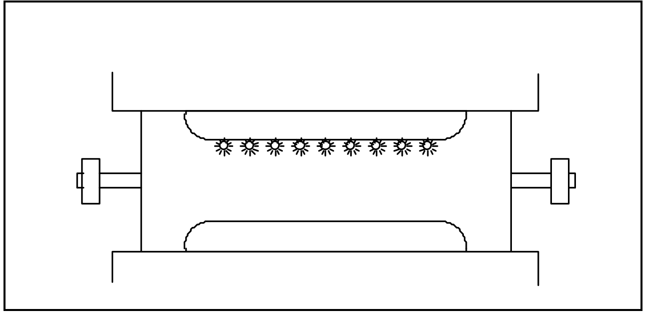


Figure 24. Preionization.

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.

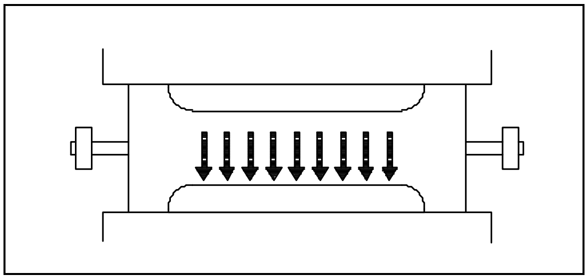


Figure 25. Gas discharge.

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

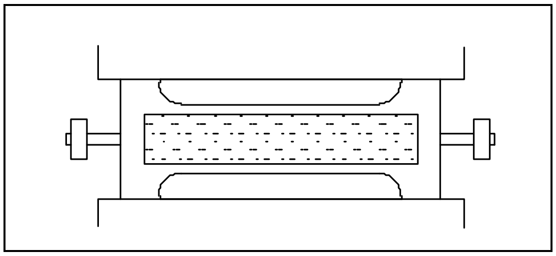


Figure 26. Formation of excimer molecules.

Step 4. The laser transition step is initiated by those photons produced by spontaneous 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.

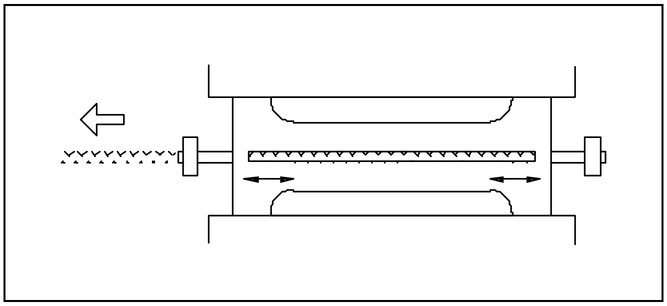


Figure 27. Laser transition.

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

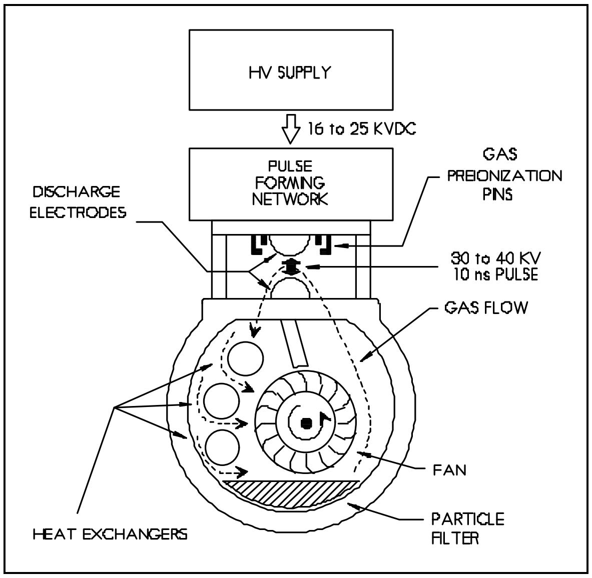


Figure 28. Cross-sectional view of an excimer laser head.

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 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 gap 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 up to 400 pulses per second are achievable.

Major Components of an Excimer Laser

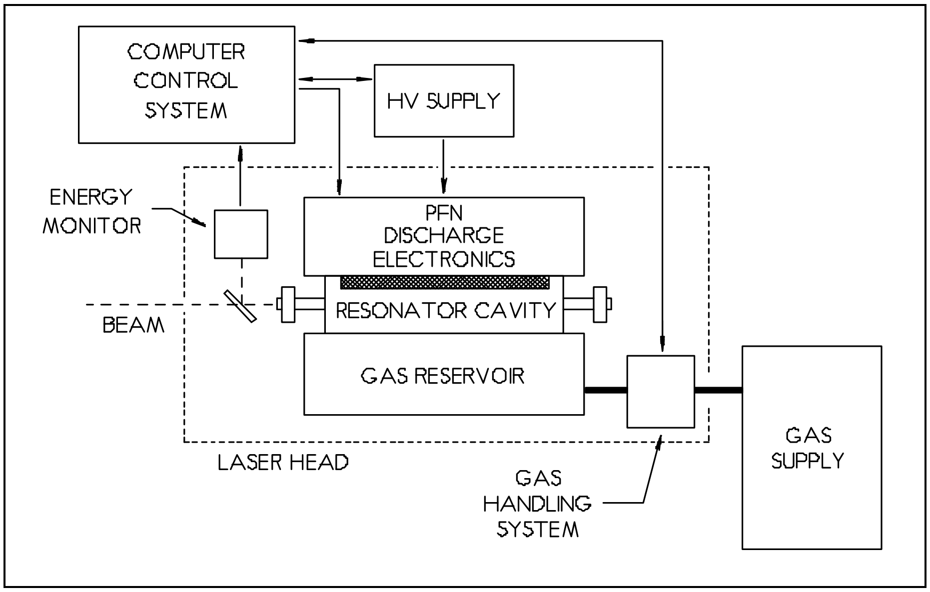


Figure 29. Block diagram of a typical excimer laser.

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

Gashandling system

- Gas manifold
- Solenoid valves
- Interlock control

Computer control system

- Automated energy stabilization
- Noise immune communication 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.

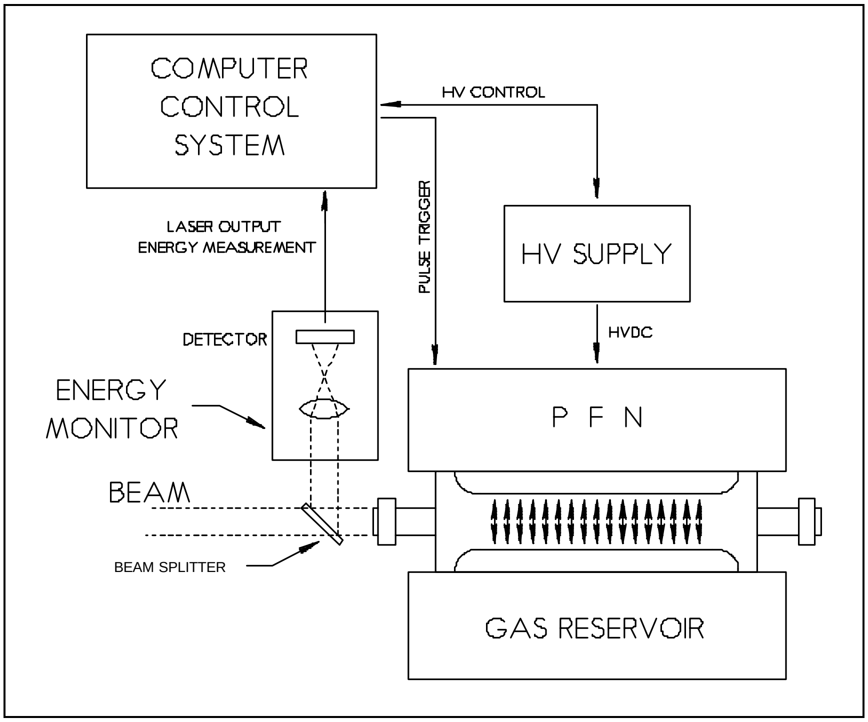


Figure 30. Typical example of excimer laser control.

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.

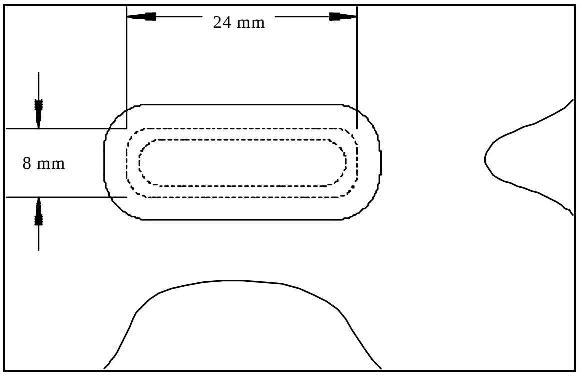


Figure 31. Beam profile of a new gas fill.

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.

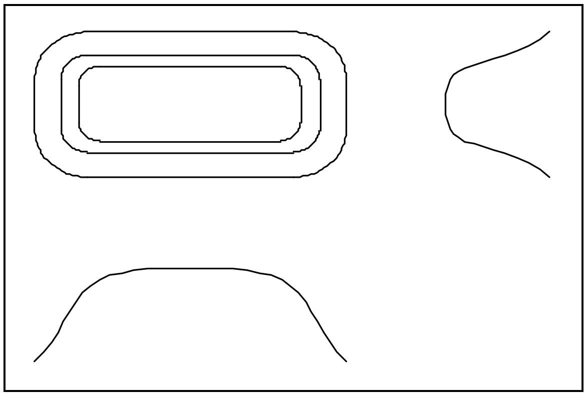


Figure 32. Beam profile of a mature gas fill.

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 surfaces as well as on other internal components. Dust on the windows absorbs 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.

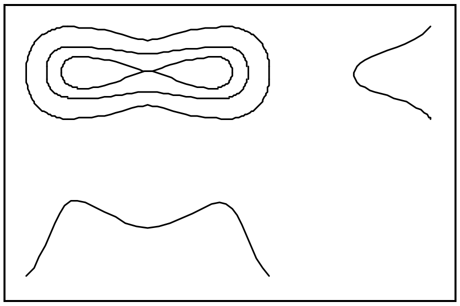


Figure 33. Beam profile of a laser with dirty optics.

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.

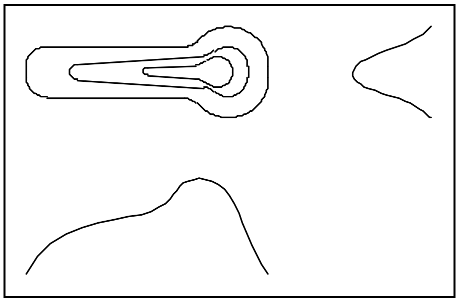


Figure 34. Beam profile of a laser with misaligned resonator optics.

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 below. 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.

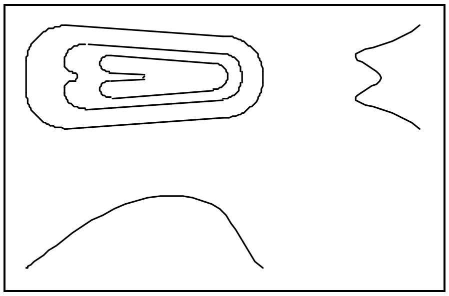


Figure 35. Beam profile of a laser with worn electrodes or preionization pins.

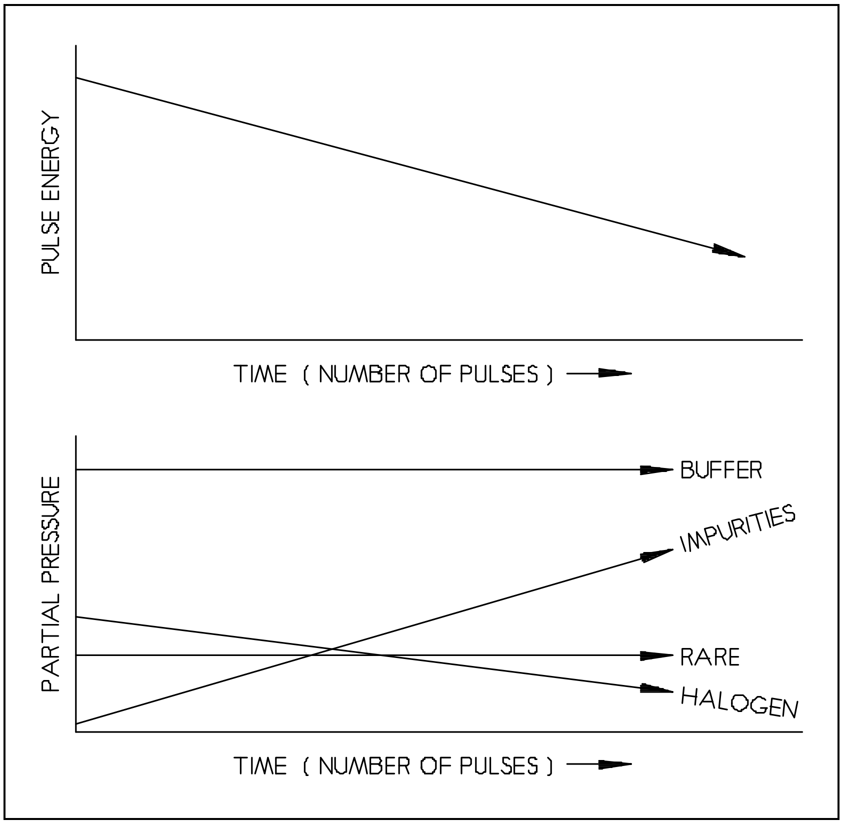


Figure 36. Halogen depletion over gas life.

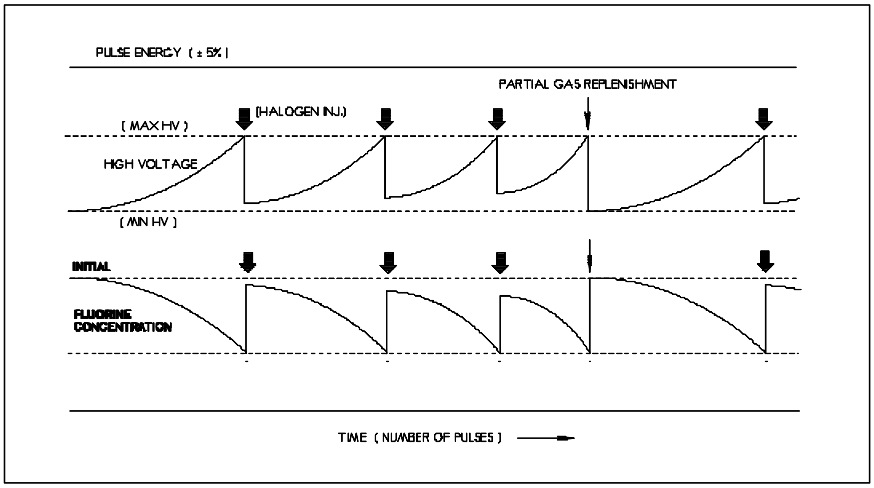


Figure 37. Gas mixture adjustments administered over gas life. The halogen injections or partial gas replenishments can be programmed by computer or executed manually.

Beam Profilometry

A typical beam profilometer employs a photoluminescent crystal as the detector. 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 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.

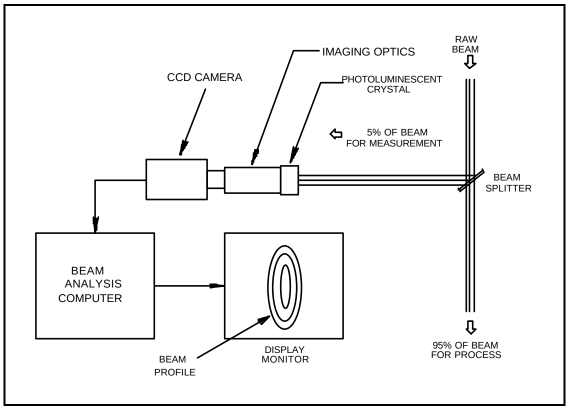


Figure 38. Block diagram of the beam profilometry process.

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 (GmbH, Goettingen, Germany), Lumonics, and MPB Technologies, Inc (Dorval, Quebec). Performance characteristics for several excimer lasers manufactured by these companies are provided below.

Parameter (KrF)	EMG 103 MSC	Lambda 1000	LPX 220i	Lumonics PM-848	Lumonics Index 886	MPB Tech PSX-100
Max pulse energy	300 mJ	300 mJ	450 mJ	450 mJ	600 mJ	3 mJ
Max average power output	55 W	60 W	80 W	80 W	30 W	0.3 W
Beam size	8 x 22 mm	8 x 24 mm	8 x 23 mm	10 x 25 mm	14 x 30 mm	2 x 2 mm
Beam divergence (mrad)	4.5 x 1.5	4.5 x 1.5	1 x 3	1 x 3	1 x 3	2 x 3.6
Pulse repetition rate (pulses/sec)	0-200	0-200	0-200	0-200	0-50	0-100

Table 10. Laser parameters for several industrial 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 hrs/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	12000
Routine parts (optics, filters)	400
Total Routine Operating Expenses	**$13000**

Laser Refurberation

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

Laser Refurb(every 1 billion pulses or approximately every year at 100 Hz)	**$17000**
Total Laser Operation and Maintenance	**$30000**

Laser refurb is required approximately every year for a laser operating 8 hrs/day. A refurb at Resonetics includes the following maintenance:

- Clean all internal surfaces of laser
- Electrodes 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
- Optical Components
- Photo-Ablation and Material Interaction with IR and UV Light
- Near-Field Imaging
- Special Imaging Techniques
- Steps to an Effective Optical Setup

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 includes 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)

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.

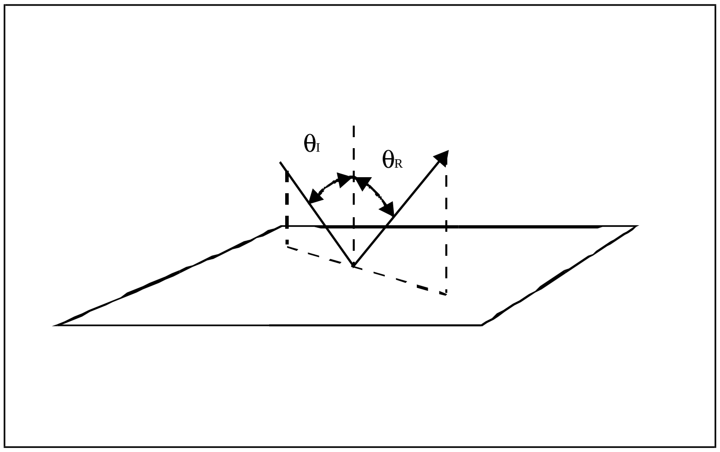


Figure 39. Angle of incidence is equal to the angle of reflection.

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

$$\frac{\sin j_1}{\sin j_2} = \text{constant}.$$

If material *1* is a vacuum, than 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.

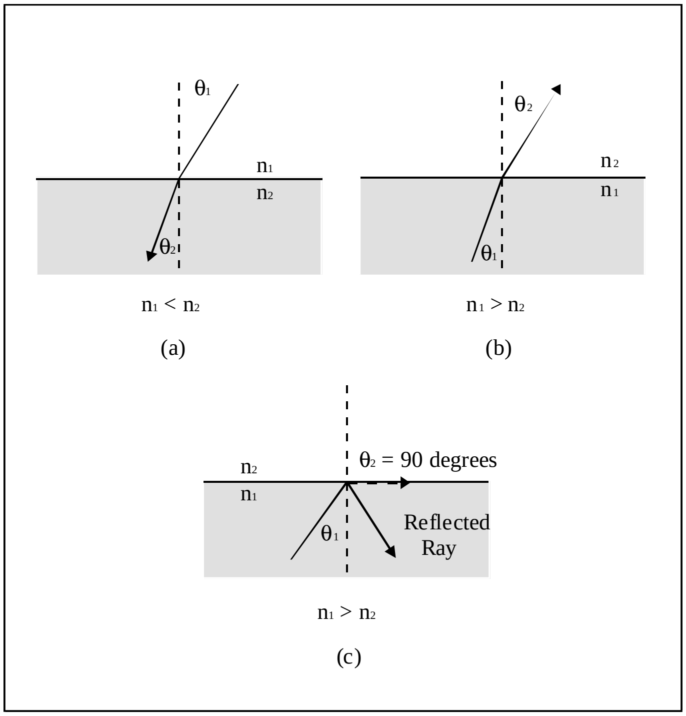


Figure 40. (a) and (b) The law of refraction for two materials of different indices. (c) Illustration of total internal reflection and critical angle.

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

$$n_1 \sin \varphi_1 = n_2 \sin \varphi_2.$$

Definitions:

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.
Index of refraction: The ratio of the speed of light in a vacuum to the velocity in a specific material (n = c/v).
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.
Beamsplitter: An optical device, usually a thin sheet of glass inserted at an angle, for dividing a beam into two or more separate beams; can be either dielectric or geometric:

dielectric beamsplitter - the beam is split by partial transmission and partial reflection through a dielectric coated optic placed in the beam path, usually at an angle.

geometric beamsplitter - the beam is split physically in two beams by a protruding mirror or prism.

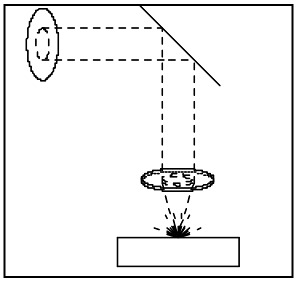


Figure 41. Focal plane

Focal plane: the plane at which all light rays converge to a point, perpendicular to the axis of a lens.
Focal Point: That point on the optical axis of a lens, to which an incident bundle of parallel light rays will converge.
Focal Length: The distance from the lens to the focal point, usually measured in millimeters.
Imaging Plane: the plane perpendicular to the axis of a lens in which an image is formed.
Plano-convex lens: A lens that converges an incident bundle of rays to a focus; convex shape on one side and flat on the other.
Mask: A field stop or aperture located at an object plane of an optical system that determines the size and shape of the image.
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.
F-Number: F-number F/# ≡ f/D, where f is the lens focal length and D is the lens aperture, is a measure of the amount of light allowed through the lens.

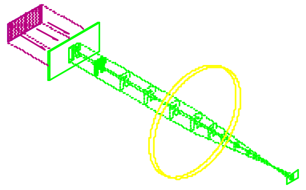


Figure 42. Imaging plane.

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

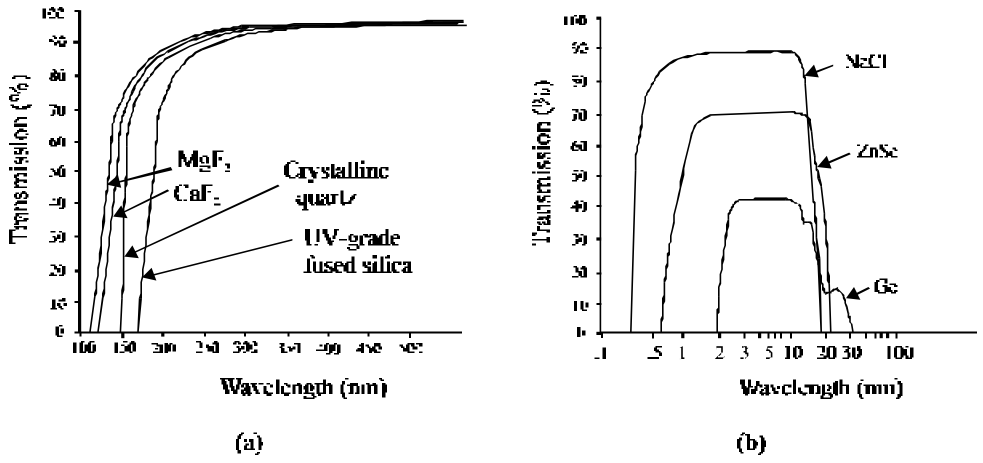


Figure 43. Transmission properties of typical (a) uv and (b) ir optical materials.

Infrared optical materials:

- Germanium (Ge)- high refractive index n = 4.0; exhibits poor transmission qualities at high temperatures > 200°C

- 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 and Nd:YLF optical components are usually fused silica.

The price of optical components depend 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, 75 mm	$325	$400	$500
1.5-inch, 100 mm	$200	$200	$325
1.5-inch, 200 mm	$140	$180	$250

Table 11. Estimated relative prices for uv lenses. In general, the shorter the focal length, the more expensive the lens.

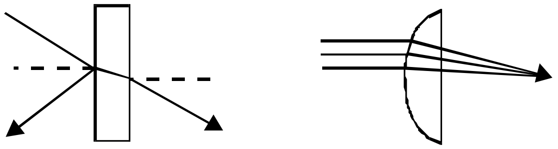
Considerations in choosing optics:

- 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. Constituency of the coatings depends on the manufacturer.

(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 44. Geometries of some typical laser optics.

The high divergence of some 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. A laser with unstable optics is difficult to align and emits a reduced energy output.

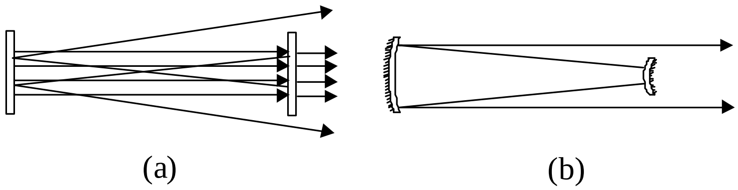


Figure 45. A stable, flat/flat resonator cavity like that shown in figure (a) delivers a low divergence of about 1 x 3 mrad. Resonator optics in this configuration, as in an excimer laser, cost nearly $900 a set. The unstable resonator cavity shown in figure (b) produces a divergence near 0.1 x 0.3 mrad but at only one-half the output as in (a). Typical price for unstable resonator optics is $3000 per set.

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

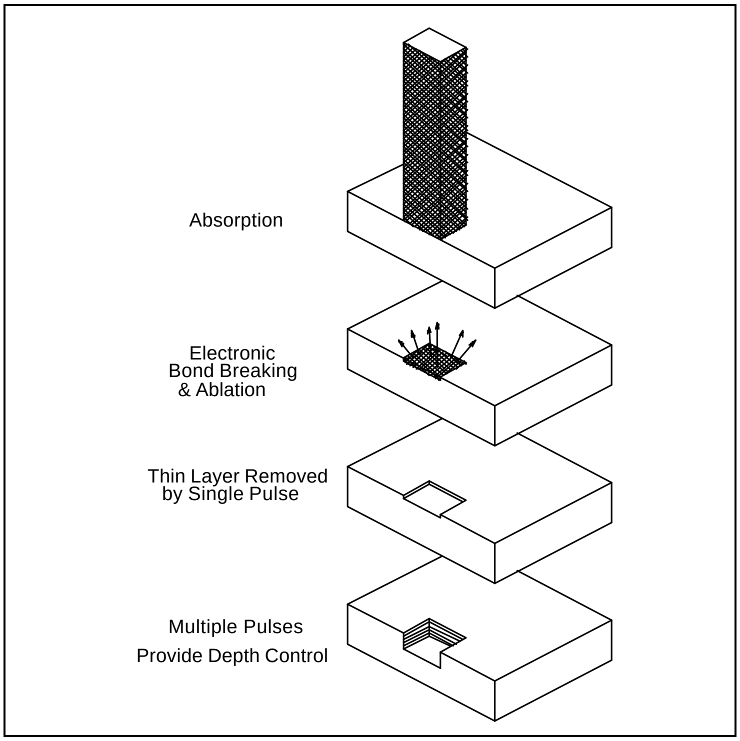


Figure 46. Photo-ablation process by exposure to uv light. A single ablation layer is typically <0.1 μm thick, due to the short uv wavelength.

Photo-Ablation

- At higher fluences, the energy from excimer uv light breaks molecular bonds in the target material surface. Each material has its own photo-ablation threshold, below which photo-ablation does not occur

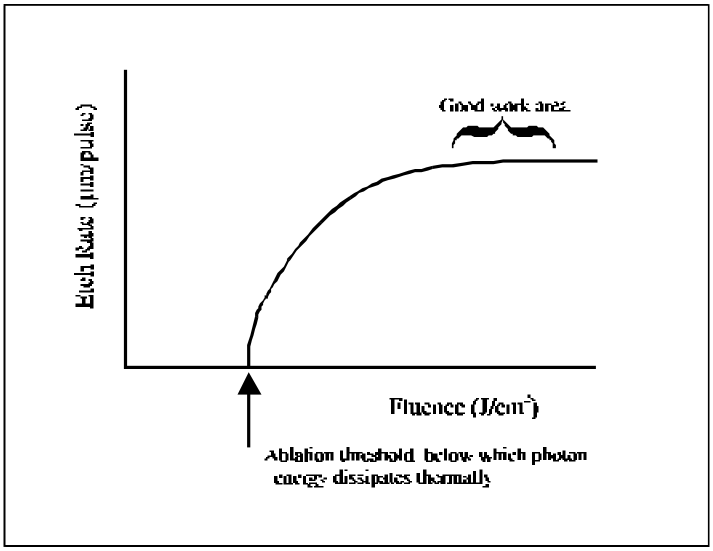


Figure 47. Etch rate vs. fluence for uv photons.

- 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

Thermal Effects

- As fluence increases, absorption depth increases resulting in larger interaction volume; greater volume results in increased heat conduction to the surrounding material.

- A 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.

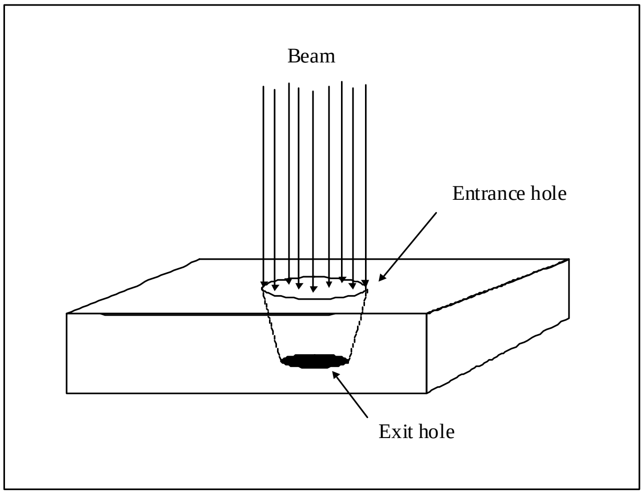


Figure 48. Taper effect in excimer near-field imaging.

Characteristics of taper:

- Taper angle is approximately 7° 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.

- 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: 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 12. 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:

$$a_T = \frac{\rho_L a_L}{\rho_T} = \frac{(0.1/2)(2)}{0.5}.$$

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 > 1 mm	193 248 308	3 to 50	300 to 5000	0.2 to 4.5	Spot imaging
Drilling	Ceramics and Hard Dielectrics	193 248 308	20 to >50	2000 to >5000	0.2 to 5	Spot imaging
Drilling	Metals	193 248 308 351	20 to >50	2000 to >5000	0.2 to >10	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 1500	0.1 to 0.3	

Table 13. Processing parameters at difference excimer wavelengths and materials.

Near-Field Imaging

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 mm**
    - **CO_2 laser 10 mm**
- In reality, practical imaging resolution is dependent on optics:
    - **Excimer laser 1-5 mm**
    - **CO_2 laser 75 mm**

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 14. 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.

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)

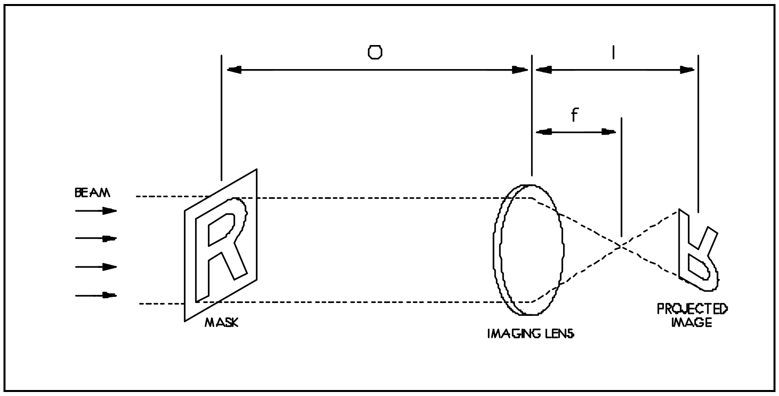


Figure 49. Theoretical near-field imaging setup.

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:

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

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:

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

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 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:

$$O = (d + 1)f, \text{ and}$$

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

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 to 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)

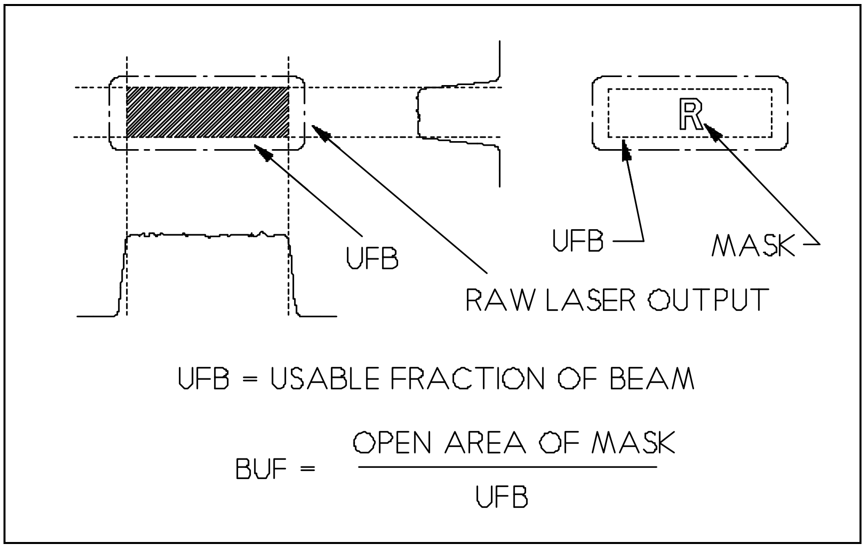


Figure 50. Beam utilization factor.

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 one 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 thin as possible.

- Sometimes more elements are acceptable if the process requires high precision and beam utilization is a secondary consideration.

Motion Controlled Beam Delivery

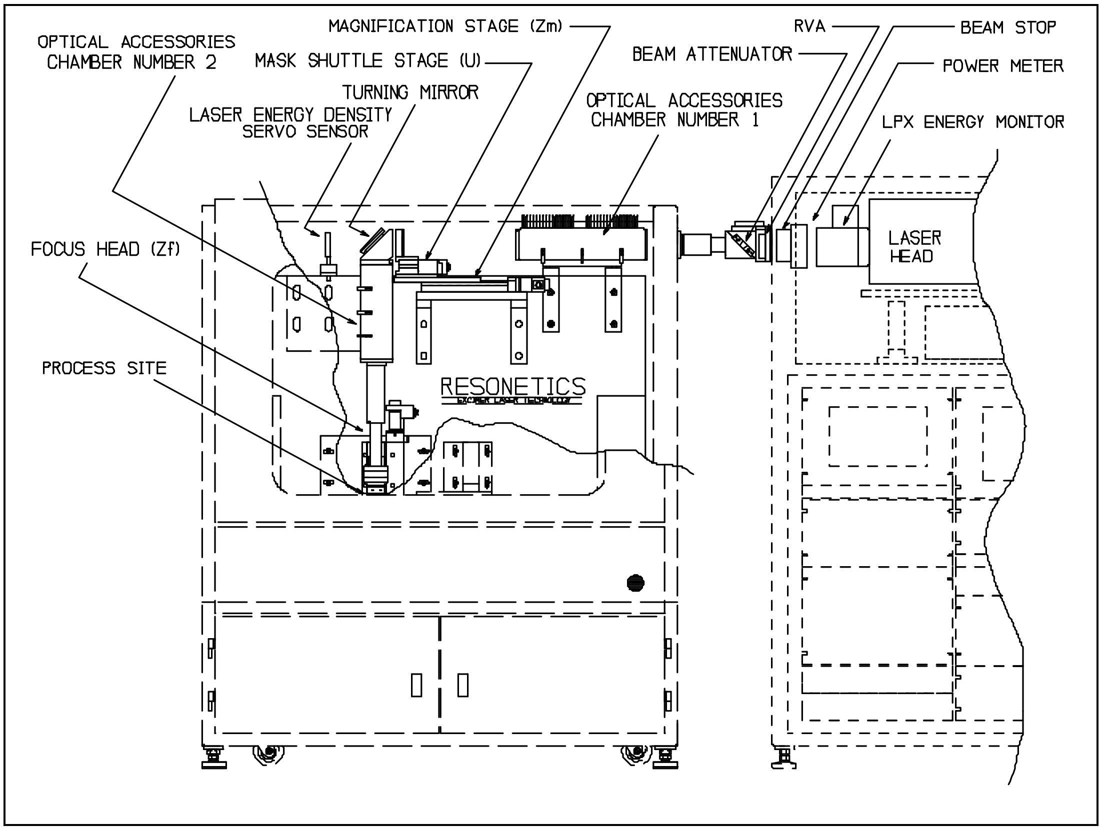


Figure 51. Motion controlled beam delivery system.

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 is 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.

Special Beam Delivery Techniques

- Scanned Illumination
- Coordinated Opposing Motion Imaging
- Contact Mask Processing
- Beam Shaping and Dividing
- Steps to an Effective Optical Setup

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. 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

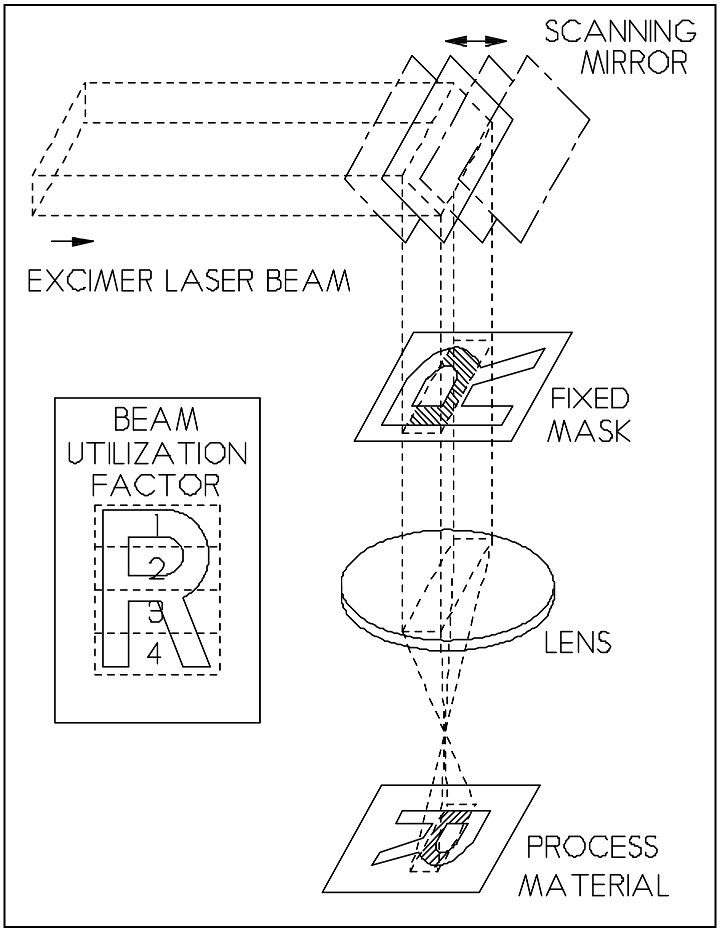


Figure 52. Scanned illumination imaging.

Coordinated Opposing Motion Imaging

In coordinated motion imaging, 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.

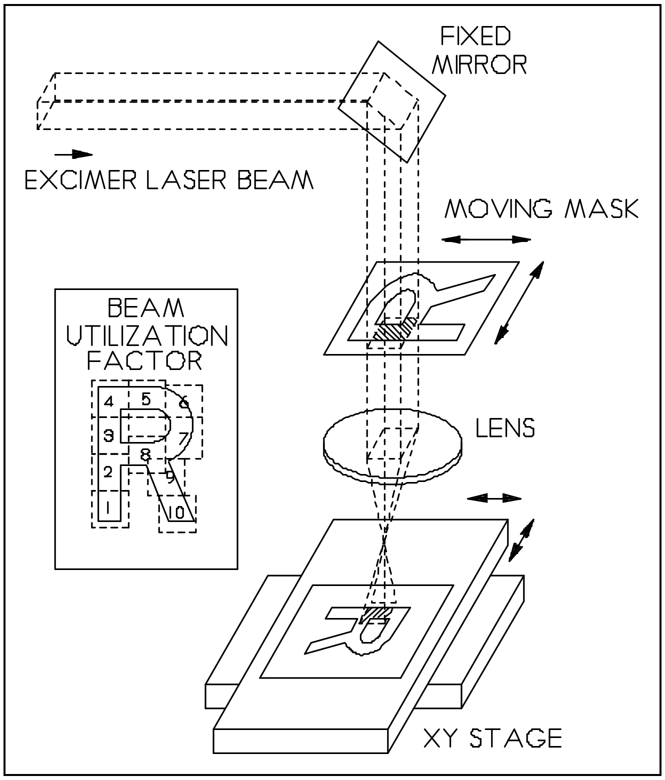


Figure 53. Coordinated Opposing Motion Imaging

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. 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

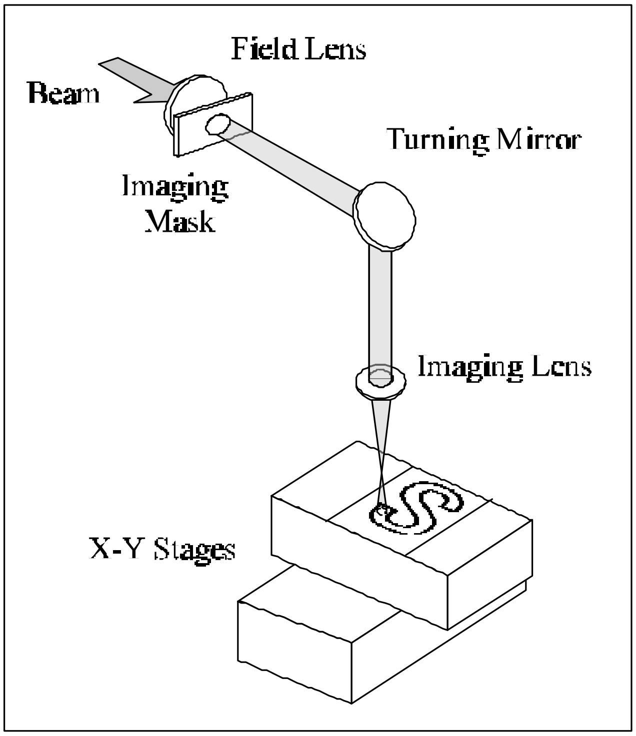


Figure 54. Direct write machining.

Contact Mask Processing

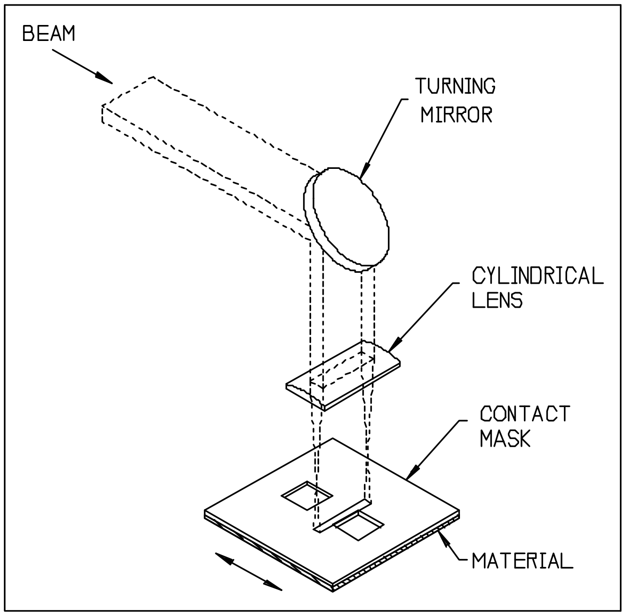


Figure 55. Contact mask processing.

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. 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 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.

Beam Shaping and Dividing

Beam shaping is the simplest technique for matching the laser beam to part features or to match the beam to the opening in an object mask.

Cautions pertaining to beam shaping techniques:

- Be careful not to increase fluence to a point where optical coatings downstream are damaged
- Be aware of the location of focal points at all times where fluences can damage optics with only a few pulses

Beam shaping with a field lens:

A field lens is a large diameter plano-convex lens with a focal length of 1 to 2 meters. The purpose of a field lens is to collimate the laser beam onto the surface of the imaging lens or another lens as shown below.

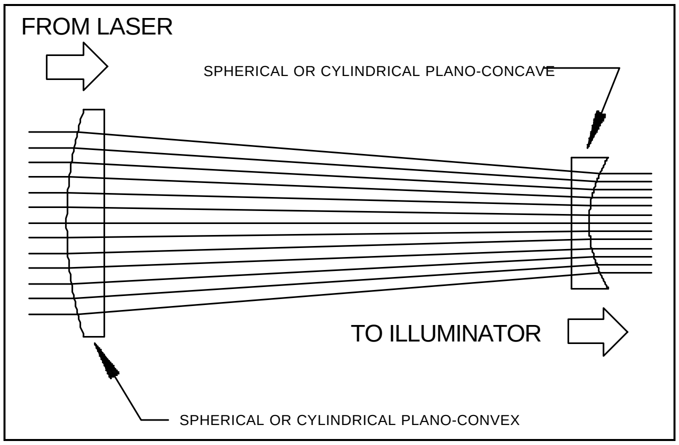


Figure 56. Beam shaping with a field lens and plano-concave lens.

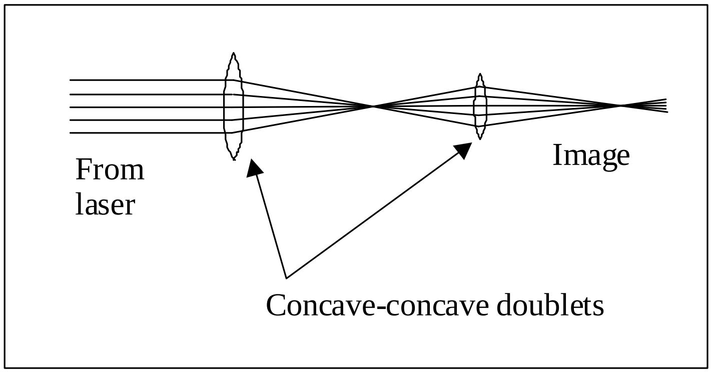


Figure 57. Keplerian telescopic lens optical configuration.

The telescope configuration shown above can be used to achieve high demagnification despite the size constraints imposed by the beam delivery system. Disadvantage, of course, is additional optical losses.

Beam Dividing

Two methods are possible: geometric or dielectric beamsplitter.

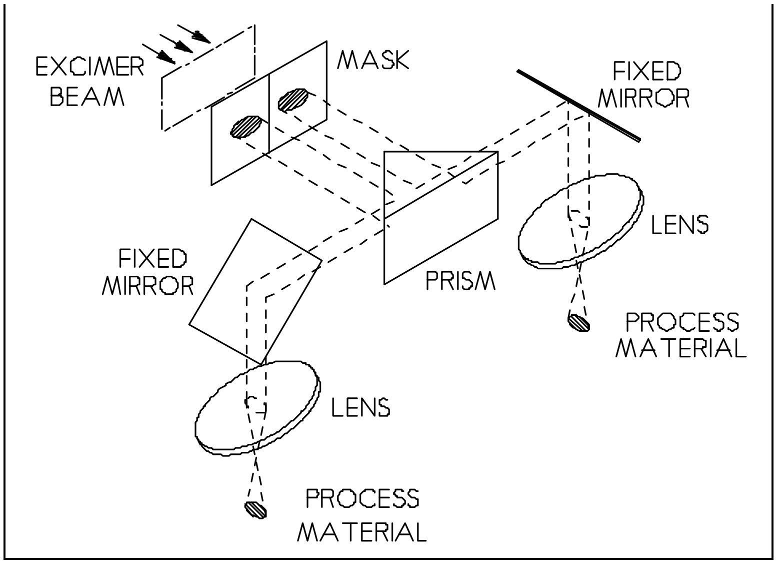


Figure 58. Geometric beam dividing using a single prism to separate the incident beam into two.

The dielectric beamsplitter method of dividing a beam is more expensive because of the coated optic. Furthermore, the dielectric coating will deteriorate over time and require replacement.

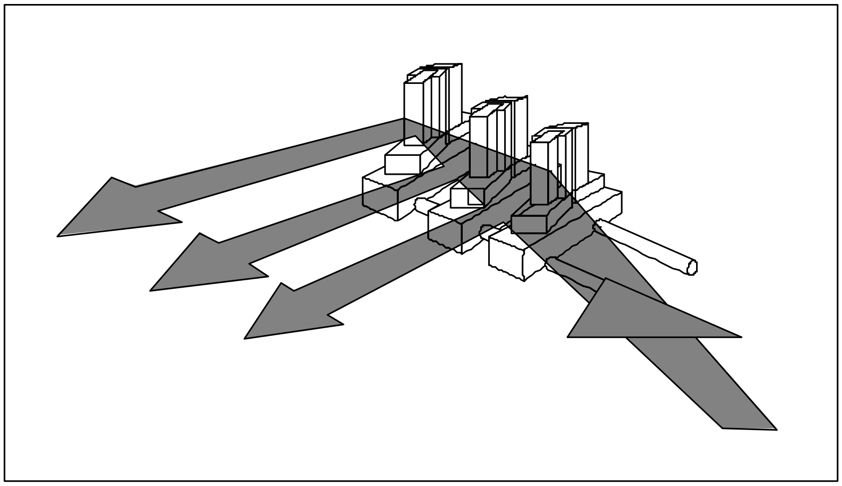
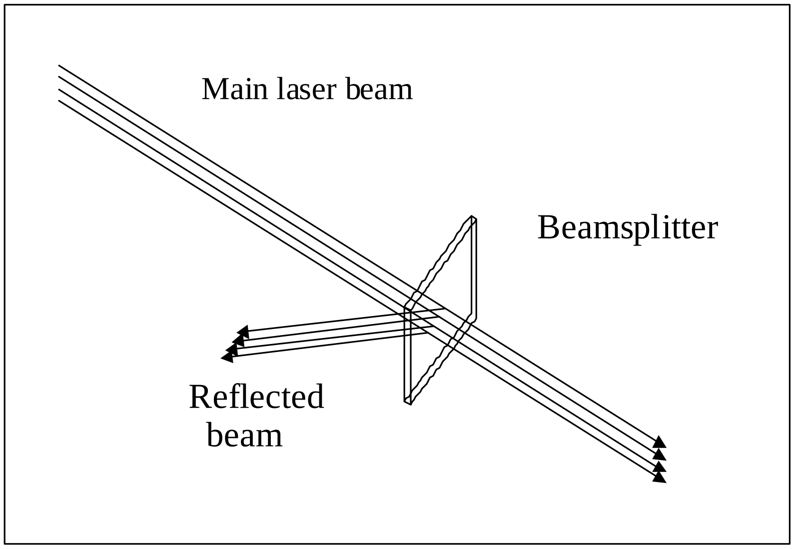


Figure 59. Geometric beamsplitter with three mirror assemblies.

Figure 60. Dielectric beamsplitter method of dividing beam. The beamsplitter is coated on the source side.



Homogenization

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

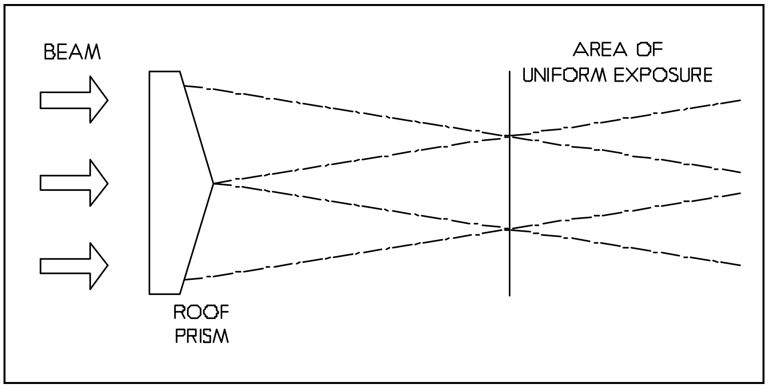


Figure 61. Simple roof prism homogenizer.

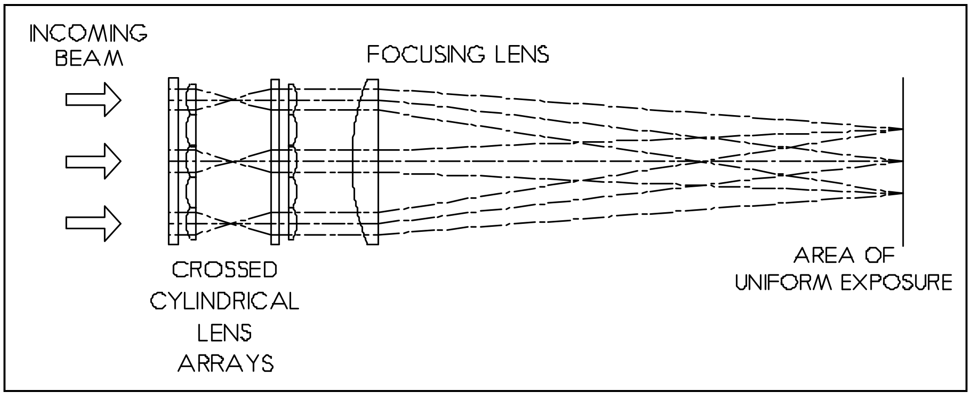


Figure 62. Sophisticated crossed cylindrical lens homogenizer.

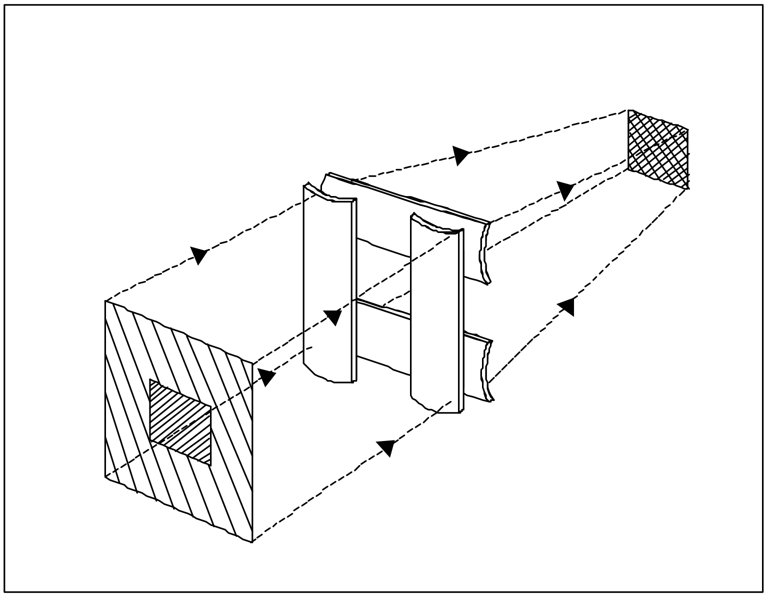


Figure 63. A homogenizer developed by Optec for use with excimer lasers. The four cylindrical lenses shown can be adjusted to give a larger or smaller center aperture.

Steps to an Effective Optical Setup

1. Determine which laser is best
    - Are machining quality and tolerances and tight enough to warrant near-field imaging, or can Nd:YLF 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 techniques**

System Integration

- Processing System Consideration
- Laser Packaging
- Part Viewing Systems
- Motion Control
- Laser Support Systems
- Safety
- Examples of Some Laser Materials Processing Systems
- Conclusion

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
    - Robotic or conveyor required to move parts?
    - Tooling or part pallets; roll-to-roll?
    - Vacuum chucks, assist gas?
    - Camera system?
    - 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
- Maintenance access features:
- Quarter turn latches on exterior panels
- Quick-change resonator windows
- HeNe laser resonator optics alignment system
- Modular subassemblies
- Quick-change 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 30 mm
    - 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

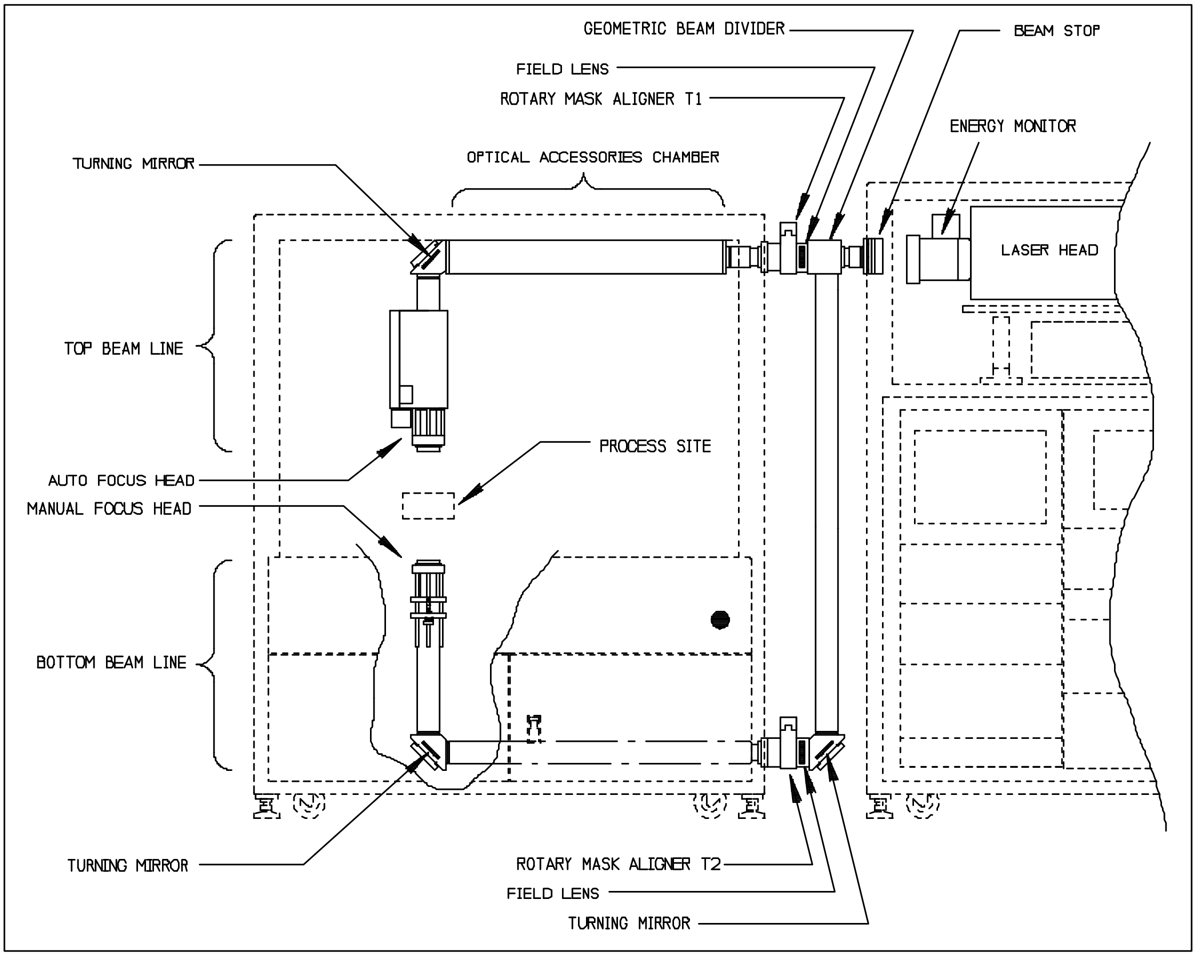


Figure 64. A beam delivery system with opposing beamlets.

One particularly interesting application that employs LWD beam delivery is the machining of ceramics. The system above splits the beam into two equal square portion, which are then passed through round apertures at a high BUF. The beamlets are demagnified by 15X, producing on-target spots of approximately 125 μm which are directed onto opposite sides of the part. Careful alignment of the two beamlets results in simultaneous double sided drilling, minimizing vibration and shock, decreasing hole taper, and doubling drilling speed.

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 15. 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 16. Advantages and disadvantages of LWD systems.

Part Viewing in LWD Systems

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 microscope part viewing system.

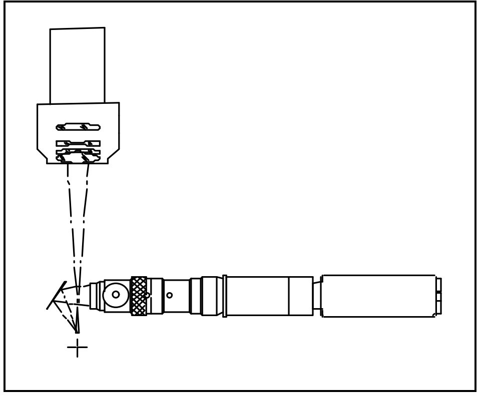


Figure 65. Off-axis viewing.

One alternative is to position the viewing system slightly off-axis to avoid obstruction of the laser beam. 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.

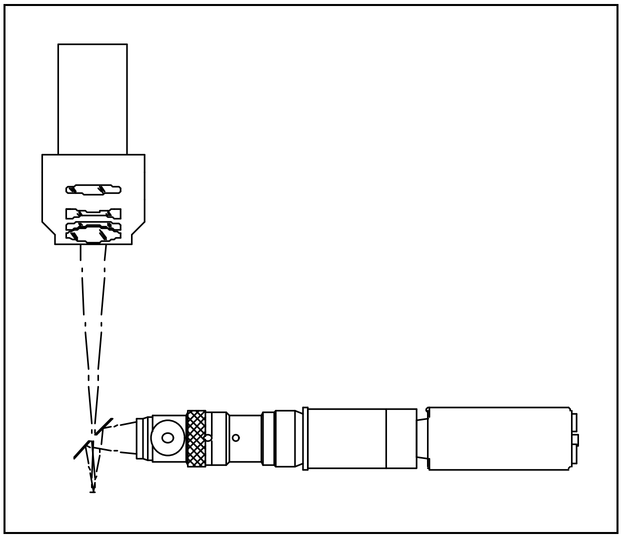


Figure 66. On-axis viewing.

Another approach to LWD part viewing is a mirror with a central opening to permit on-axis viewing. 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.

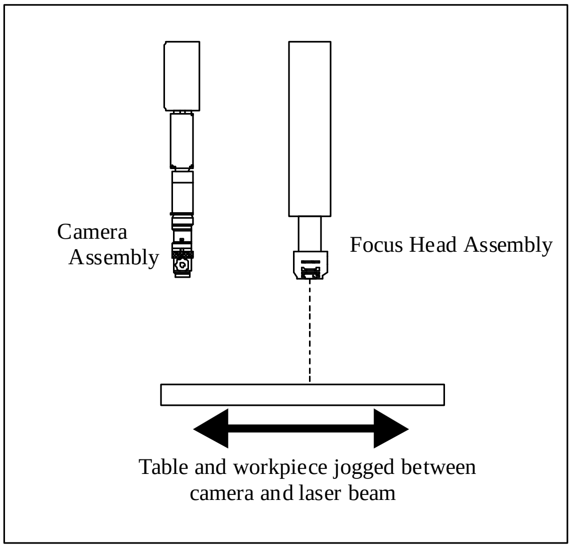


Figure 67. On-axis, off-line viewing setup.

A third option in part viewing is the on-axis, off-line viewing setup illustrated above. 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.

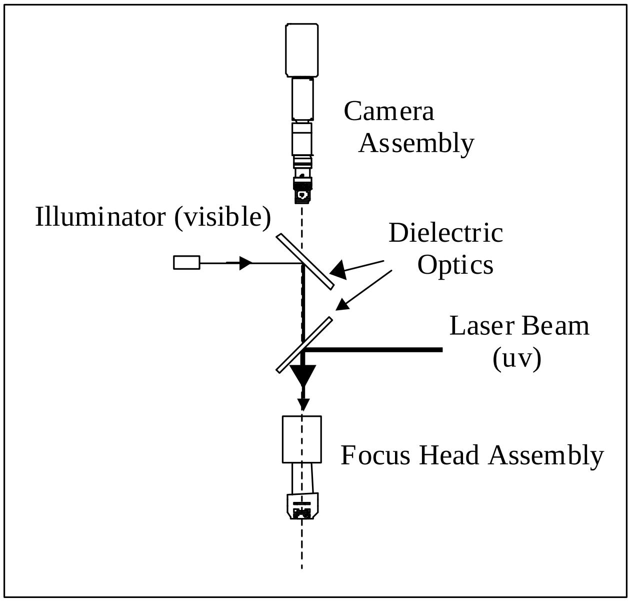


Figure 68. On-axis, on-line viewing setup.

Still another part viewing approach is the on-axis, on-line viewing setup shown above. 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.

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.

Objective Type	Multi-element Refractive
Resolution	0.25 to 0.5 µm
Field size	up to 150 µm
Complexity	High
Cost	High
Losses	High
Notes	Elements are AR coated to reduce losses

Table 17. Viewing parameters using microscope imaging.

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 18. Advantages and disadvantages of microscope viewing.

Motion Control

There are two fundamental types of motion systems: stepper motor or servo motor. Both stepper motors and servo motors 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 mm) when microstepping incorporated into system**
- **Stiff stationary holding torque**
- **High operating torque**
- **Ideal for low speed applications, i.e. micromachining**

Some disadvantages of stepper motor systems 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.

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 IO can be controlled by many controller cards
- Touch screen control

Stepper Motor Systems

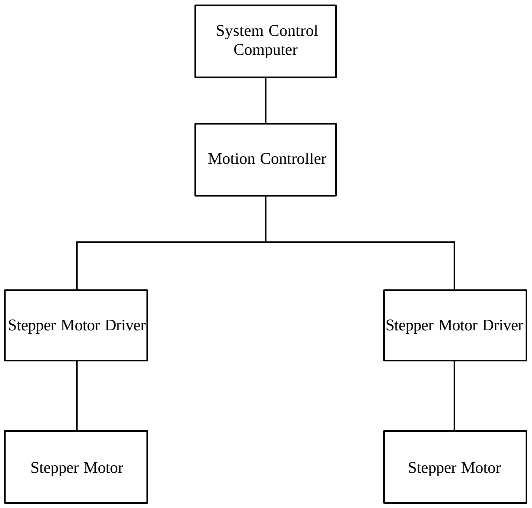


Figure 69. Block Diagram of a typical stepper motor drive system with no encoder feedback. The motion controller is usually configured as a circuit board inside the computer.

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

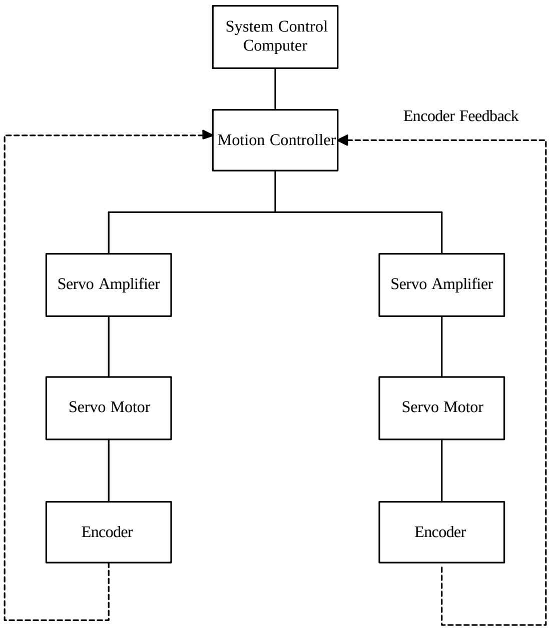


Figure 70. Servo motion control system with encoder feedback.

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

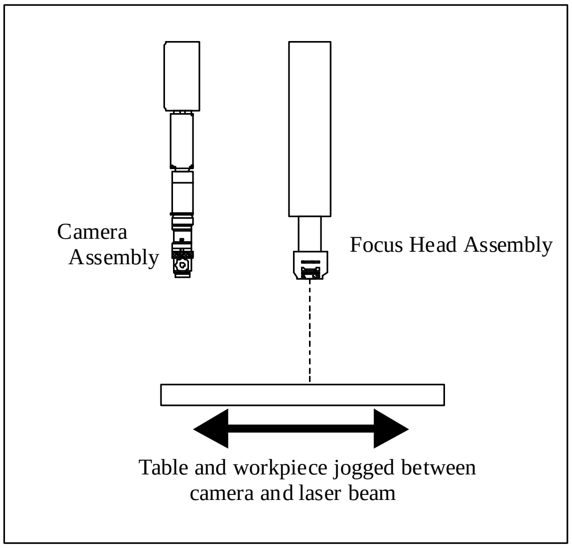
- Large motion control systems may pose mechanical hazards to people
- Mechanical guards
- Documented maintenance procedures

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



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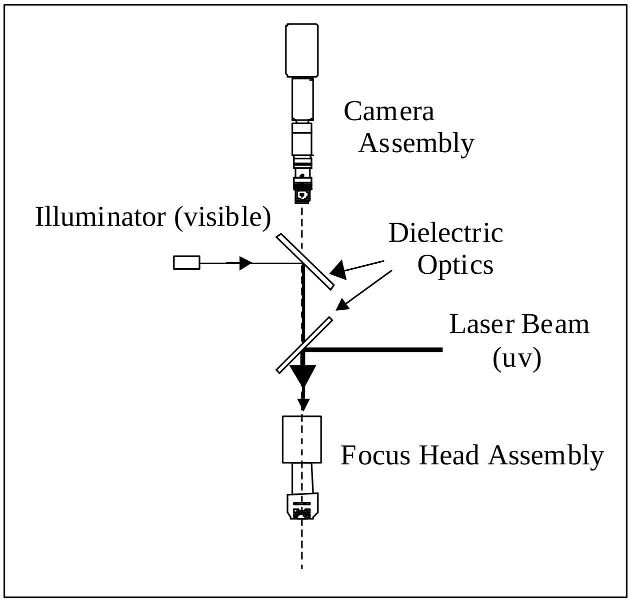

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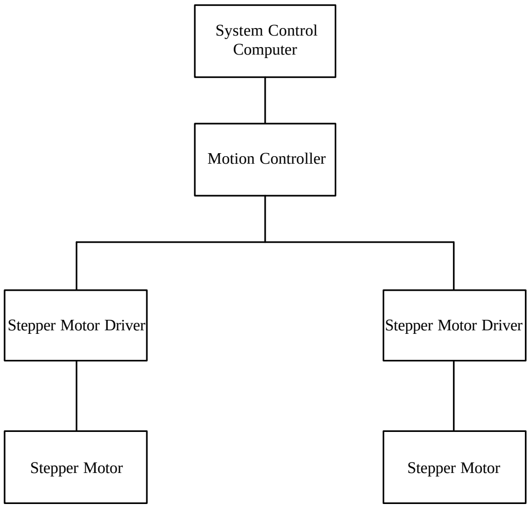

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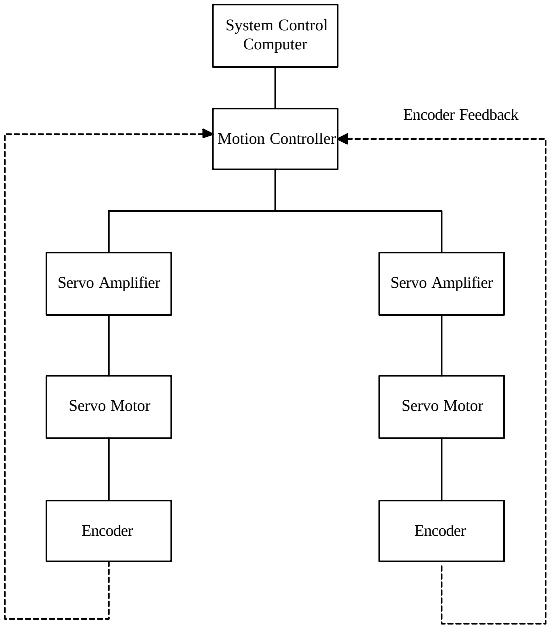

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