Laser Beam Machining

ME688: Advanced Machining Processes
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Introduction

- Lasers are everywhere!
- Some applications
  - Cutting
  - Welding
  - Bending
  - Hardening
  - Cladding
  - 3-D printing
  - Laser Shows Yes!

Introduction

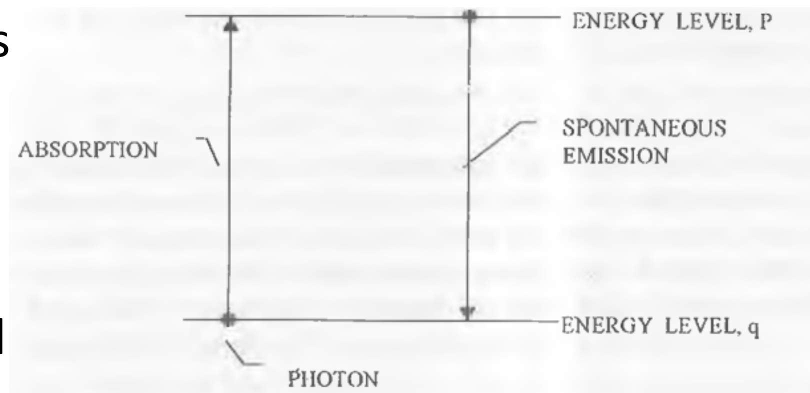
- A tremendous amount of energy released due to collision of oscillating, high energy-level atoms with electromagnetic waves having resonant frequency
- These waves absorb energy from the atoms and become highly powerful
- MASER- Microwave Amplification Stimulated Emission of Radiation
- Amplification of ordinary light waves based on similar principle
- Transmission of light waves with constant frequency and wavelength without interference)
- Laser- Light Amplification by Stimulated Emission of Radiation

Laser History

- 1917 - Albert Einstein: Theoretical prediction of stimulated emission
- 1946 - G. Meyer-Schwickerather: first eye surgery with light
- 1950 - Arthur Schawlow and Charles Townes: Emitted photons may be in the visible range
- 1954 - N.G. Basow, A.M. Prochorow, and C. Townes: ammonia maser
- 1960 - Theodore Maiman: first laser (ruby laser)
- 1964 - Basow, Prochorow, Townes (Nobel prize): quantum electronics
- 1970 - Arthur Ashkin: laser tweezers
- 1971 - Dénes Gábor (Nobel prize): holography
- 1997 - S. Chu, W.D. Phillips and C. Cohen-Tanoudji (Nobel prize): Atom cooling with laser

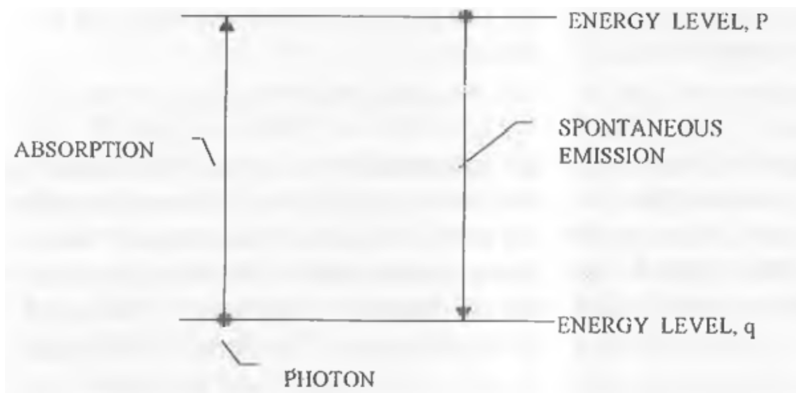
Absorption of Light

- Light energy of a particular frequency can be used to stimulate the electrons in an atom to emit additional light with exactly the same characteristics
- An atom, initially in any of the excited states, does not remain forever in that sate (or energy level)
- An atom at 'q ' energy level has light of right frequency acting on it, it absorbs photons of that light
- The transition takes place from lower energy level 'q ' to higher energy level 'p'
- This phenomenon of the movement of an atom to the higher energy level is called absorption



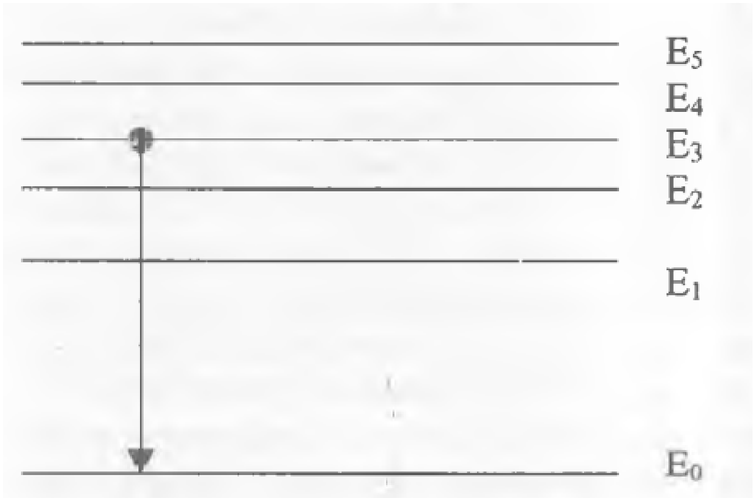
Emission of Light

- On the other hand, transition of an atom from the higher energy level ‘p ’ back to the lower energy level ‘q ’ is known as emission
- The emission could be one of the two kinds
  - Spontaneous emission (independent of light intensity)
  - Stimulated emission (influenced by the intensity of light)

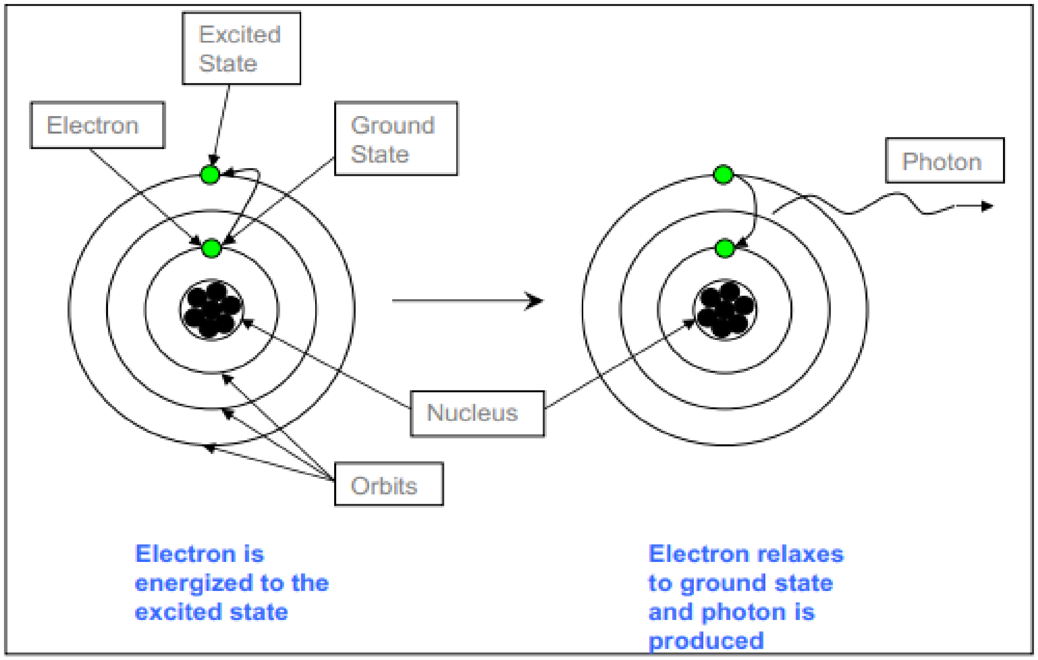


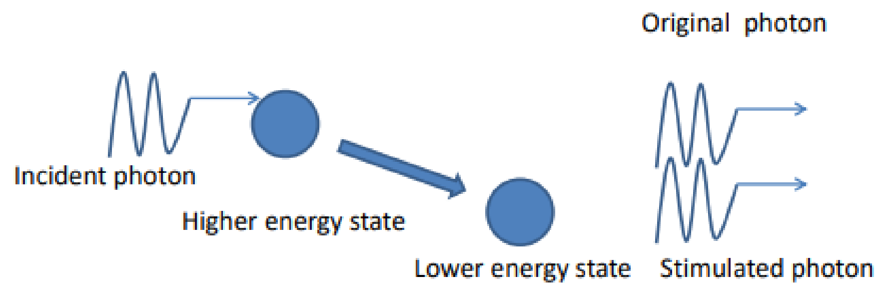
Stimulated Emission

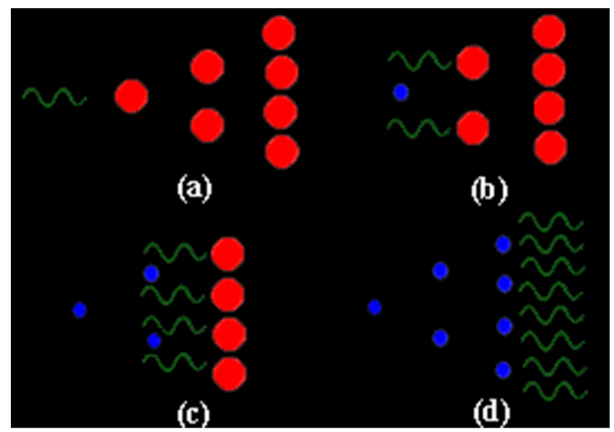
- Let an atom (or molecule) be brought to high energy level by an outside energy source (say, heat, light, chemical, etc)
- Now, if it is allowed to decay back to its ground state energy level (E0), a photon (unit of light) is released
- If this photon comes in contact with another molecule or atom at high energy level (E3) then this atom will also decay back to ground state releasing another 'photon'
- This chain of events would produce photons having same characteristics (viz wavelength, phase, direction and energy)
- This sequence of triggering clone photons from stimulated atoms (or molecules) is known as stimulated emission
- Stimulated emission forms the basis of laser operation



Principle


Excited State
Electron
Ground State
Photon
Nucleus
Orbits
Electron is energized to the excited state
Electron relaxes to ground state and photon is produced


Original photon
Incident photon
Higher energy state
Lower energy state
Stimulated photon

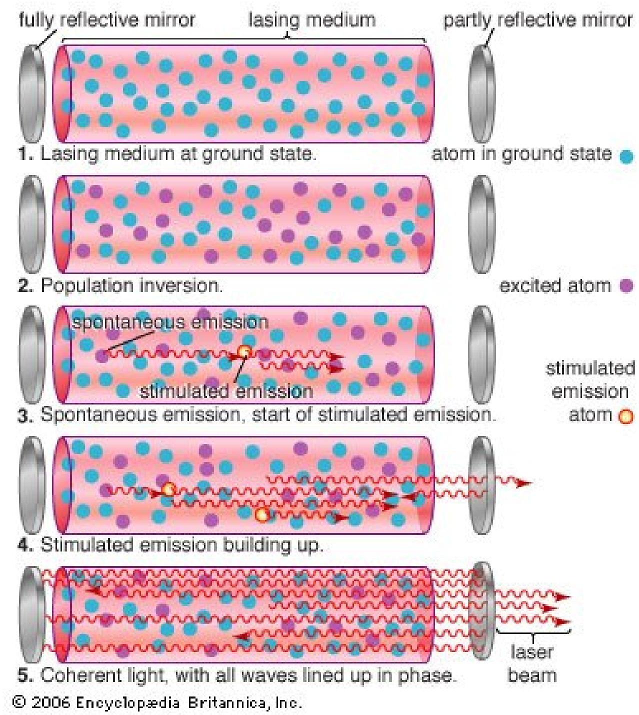

(a)
(b)
(c)
(d)

Population Inversion

- Atoms are in the ground state at normal room temperature and few atoms are in the higher excited state
- External energy supplied to the atoms such that there will be large number of atoms in higher excited state than in the lower energy level
- This situation is called the population inversion
- The external energy source which generates this situation is called Energy Pump
- As the population inversion is nonequilibrium state, the situation will not exist for long time and the atoms from the higher excited state soon transferred to lower energy levels following the thermal equilibrium population distribution
- To get continuously population inversion and subsequently stimulated emission, excitation by external energy source is the basic requirement of laser generation process

Amplification of Light in Laser

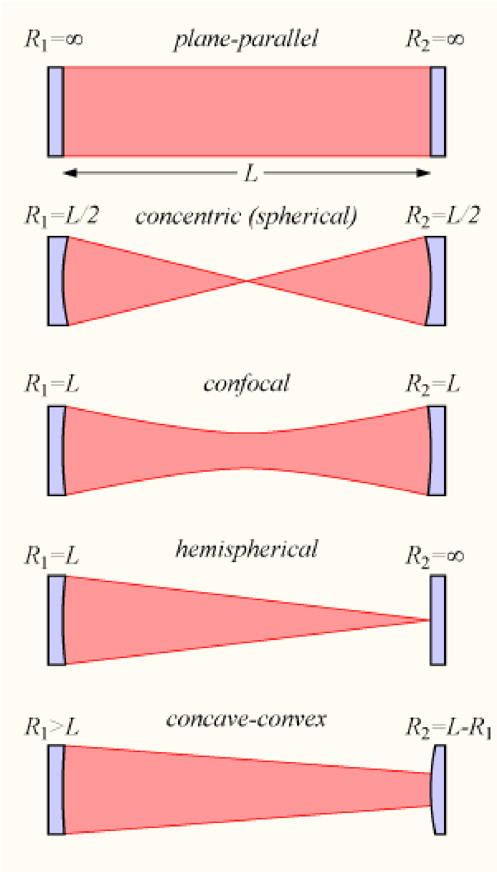
- The amplification of light in a laser is accomplished by an optical resonator, which is composed of a cavity with the lasing medium set between two high precision, aligned mirrors
- One is fully reflective, and the other is partially transmissive to allow for the beam output
- The mirrors channel light back into the lasing medium; as the photons pass back and forth through the lasing medium, they stimulate more and more emissions
- The mirrors to stimulate more emissions, so that the cavity will only amplify those photons with the proper orientation, do not redirect photons, which are not aligned with the resonator.



Optical Resonator

- Basic designs components
  - Totally reflecting mirror
  - Partially reflecting mirror
  - Mirror materials: ZnSe, GaAs and CdTe for $C0_2$ lasers, BK7 fused Silica
  - Key parameters: R1, R2, L
  - Multiple configurations

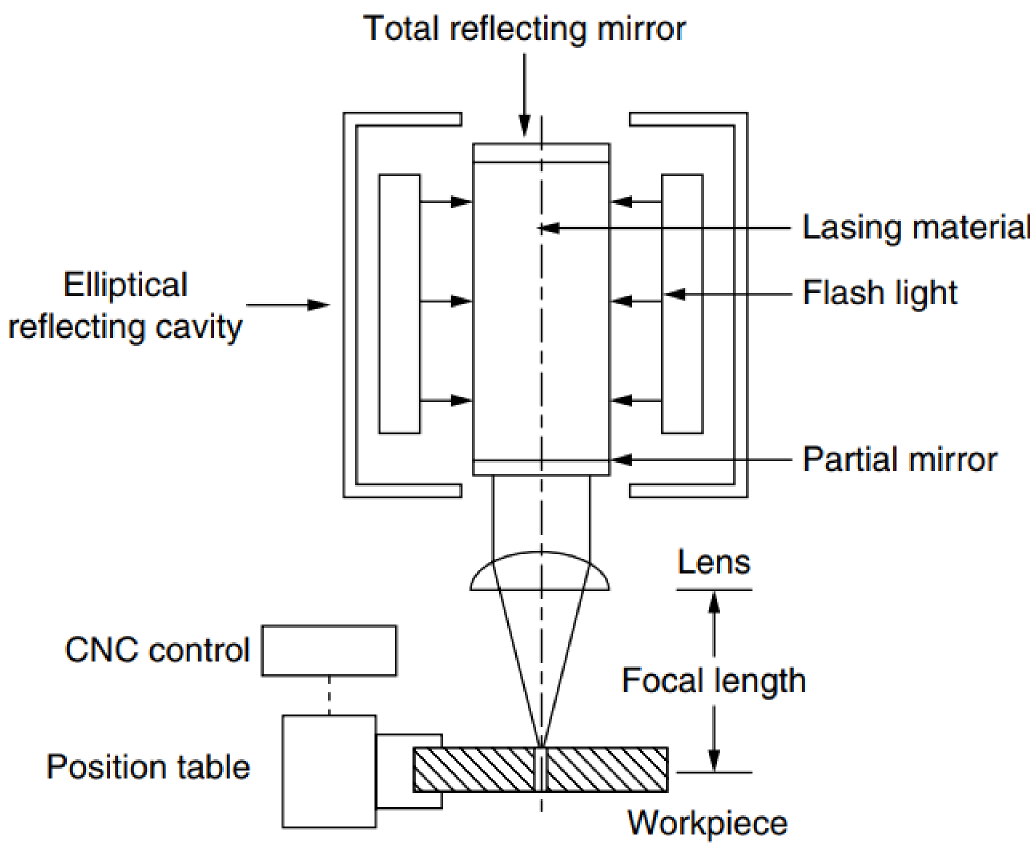
Stability??



Laser Properties

- Laser light is monochromatic, i e its wavelength occupies a very narrow, portion of the spectrum
- Hence, a simple lens is able to focus and concentrate laser light to a spot of much smaller diameter and much higher intensity than that obtained by other types of light
- Laser light is coherent in nature (it travels in phase). Hence, it gives higher focused intensities than normal light which is incoherent in nature
- The low divergence rate of lasers is also responsible for high intensity of light
- Thus, laser beam is a light source having unique properties like high monochromaticity, high degree of coherence, high brightness, high peak power, high energy per pulse, and very small size of the focused spot

LBM Setup



Total reflecting mirror
Lasing material
Elliptical reflecting cavity
Flash light
Partial mirror
Lens
CNC control
Focal length
Position table
Workpiece

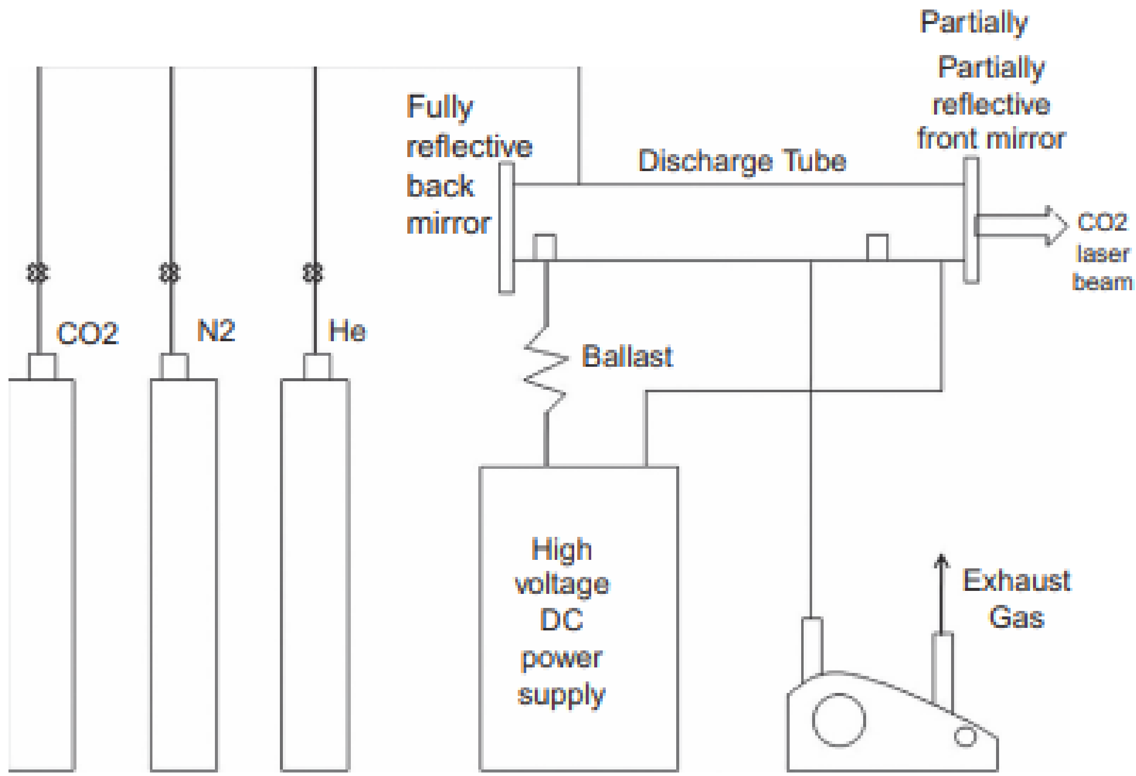
Types of Laser

- Most of the lasers can be classified into following categories
  - Gas lasers (CO_2, He-Ne, Excimer)
  - Solid state lasers (Ruby, Nd:YAG, Fiber)
  - Diode lasers
  - Dye lasers
  - Ultra-short pulsed lasers

Gas Laser: CO_2 Laser

- CO_2 laser is an electrically excited gas discharge laser
- Use of three gases: carbon dioxide (2–5%) as the active medium, nitrogen (10– 55%) as a charging medium and helium (40–88%) as coolant
- Nitrogen gases are charged to transfer energy to the carbon dioxide molecules by means of collisions
- The carbon dioxide molecules are excited to higher energy level and then come to ground state by emitting laser light
- CO_2 lasers operate in the infrared region, 10.6µm
- The amplification of laser light takes place in the optical resonator
- The output power of carbon dioxide laser beam varies from 10W to 45 kW
- CO_2 laser can be obtained in the continuous wave (CW) form as well as pulsed wave (PW) form
- CO_2 lasers are frequently used in industrial applications for cutting and welding and surface engineering

Gas Laser: CO_2 Laser



Excimer Laser

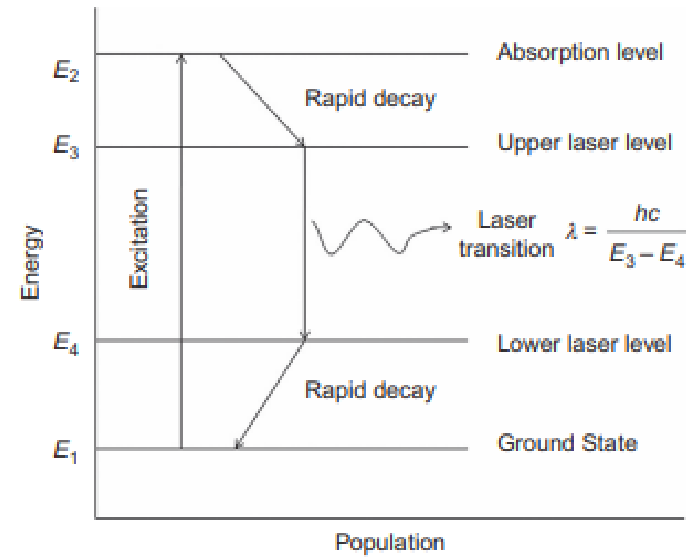
- The name Excimer is an acronym for Excited Dimer and is a gas laser
- Two gas molecules are excited by energy released by electrical discharge
- Excited Dimer or excimer molecules are formed by the electronic charging of a mixture of halide gas (fluorine or chlorine) with a rare gas such as argon, krypton or xenon
- No excited dimer can stay for long time at this excited state
- After some time, the excited molecules are separated out with releasing some energy in the form of beam of photon which has called as excimer laser
- The excimer laser is an ultraviolet (UV) laser
- The operating medium is a gaseous mixture of a noble gas and a halide gas mixed with either He or Ne as a buffer gas

Excimer Laser

- The maximum repetition rate for existing industrial excimer laser generally varies between 100 and 250Hz, although some units may work outside these limits
- Each Laser pulse has an energy of between 300 to 1000mJ depending upon the choice of laser and gas mixture
- This translates to average powers of between 30 to150W. However, since the pulse lengths are short, around 25 ns, peak powers can be as high as 25MW
- Moreover, the energy is delivered in very short periods of time (typically 25 ns), making it possible to remove material in small increments
- In comparison to other lasers, excimer laser beams are short pulsed, shorter wavelength, have small coherence and high divergence

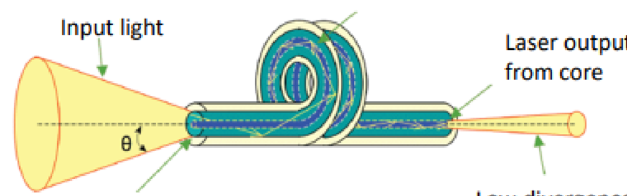
Solid state lasers: Nd: YAG Laser

- Crystalline YAG (Yttrium Aluminium Garnet) $Y_3Al_5O_{12}$ as a host material
- The Nd^{3+} ions substitute yttrium ion sites in the lattice with a maximum doping level of around 2%
- This is a typical four-level energy laser system
- Output of Nd:YAG laser can be continuous or pulsed
- The light source for pumping depends on the absorption characteristics of the crystal



Fiber Laser

- Excitation erbium or ytterbium as active laser medium within the fiber optic cable from its ground state to an excited state (population inversion) and stimulated emission of photons in that medium
- Doped fiber amplifiers provide light amplification without lasing
- Pumped by diode lasers



Laser	Type	Wavelength	CW or Pulsed	Output Power	Applications
ArF, Krf, XeCl, Xef	Gas (excimer)	193 nm, 248 nm, 308 nm, 353 nm	ns	10 W	UV lithography, laser surgery, LASIK, laser annealing
Nitrogen	Gas	337 nm	ns	100 mW	Dye laser pumping, measuring air pollution
Dye	Liquid	400-1000 nm	CW-fs	1 W	Spectroscopy, laser medicine
GaN	Semiconductor	410 nm	CW, ns	50 mW	Optical disc (Blu-ray) reading/recording
Argon-ion	Gas	488 nm	CW	10 W	Microscopy, retinal phototherapy, lithography
HeNe	Gas	632.8 nm	CW	10 mW	Interferometry, holography, barcode scanning
AlGaInP, AlGaAs	Semiconductor	630-900 nm	CW, ms	10 mW, 10 W	Optical disc (CD, DVD) reading/recording, laser pointers, solid-state laser pumping, machining
Ti:Saph	Solid-state	650-1100 nm	CW-fs	10 W	Spectroscopy, LIDAR, nonlinear frequency conversion, multiphoton microscopy
Yb:YAG	Solid-state	1030 nm	CW-ps	W-kW	Materials processing, optical refrigeration, LIDAR

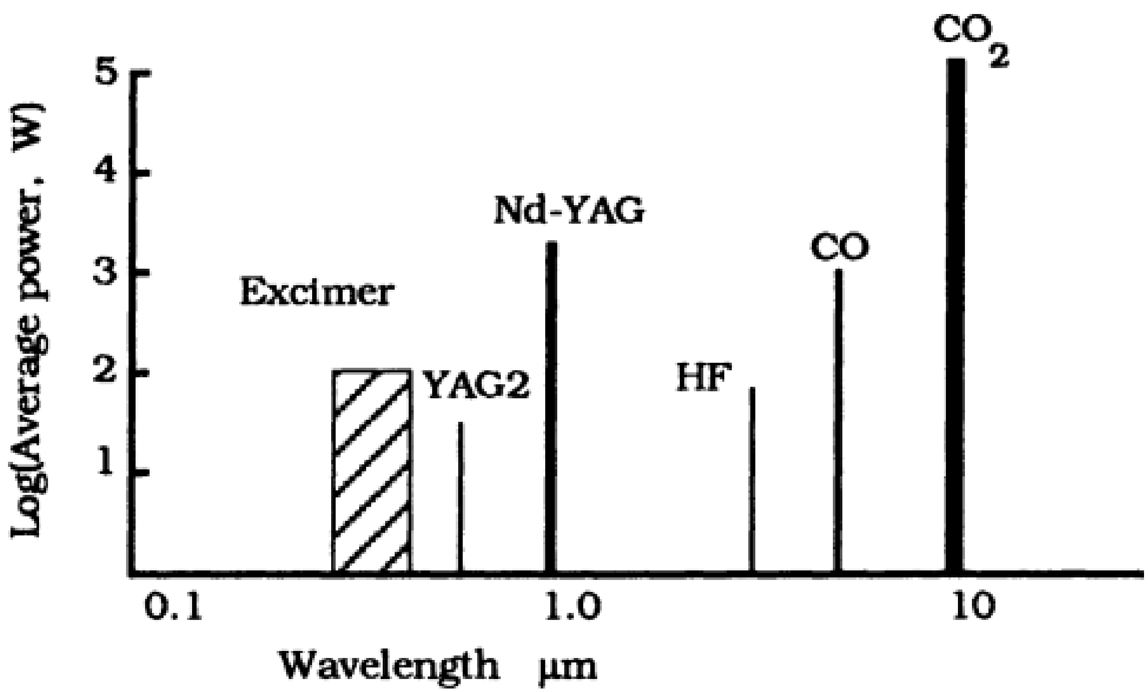
Laser	Type	Wavelength	CW or Pulsed	Output Power	Applications
Yb-glass	Fiber	1030 nm	CW-fs	W-kW	Materials processing, ultrashort pulse research, LIDAR
Nd:YAG	Solid-state	1060 nm	CW-ps	W-kW	Material processing, rangefinding, surgery, tattoo/hair removal, pumping other solid-state lasers
ND:glass	Fiber	1060 nm	CW-fs	W-kW	Material processing, pumping other solid-state lasers, extremely high power/energy systems for laser fusion
InGaAs, InGaAsP	Semiconductor	1100-2000 nm	CW, ms	mW-W	Telecommunications, solid-state laser pumping, machining, medical
Er-glass	Fiber	1530-1560 nm	CW	10 W	Optical amplifiers for telecommunications
Tm:YAG, Ho:YAG	Solid-state	2000-2100 nm	µs, ns	W	Tissue ablation, kidney stone removal, dentistry, LIDAR
Cr:ZnSe	Solid-state	2200-2800 nm	CW, fs	10 W	MWIR laser radar, missile countermeasures, ultrafast and high-resolution spectroscopy, frequency metrology
CO_2	Gas	10600 nm	CW, µs	kW	Material processing, surgery, dental laser, military lasers
Yb-glass	Fiber	1030 nm	CW-fs	W-kW	Materials processing, ultrashort pulse research, LIDAR

Wavelengths of Solid-State Lasers

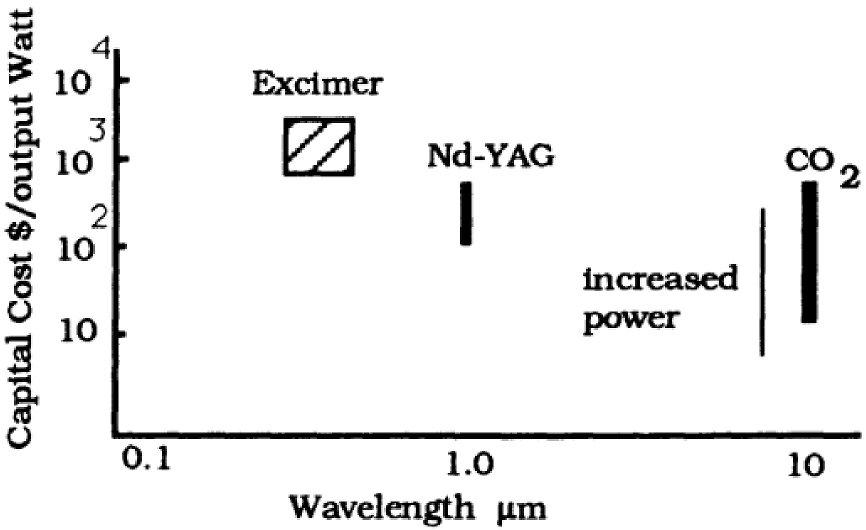
Table 1.4	Wavelengths accessible with common solid state lasers							
Laser Type	Wavelength (μm)							
	0.1	0.2	0.3	0.4	0.6	0.8	1.0	2.0
Holmium-YAG							*	*
Erbium-Glass					*		*	
Nd-YAP		*	*	*			*	
Nd-YAG		***	*	* **	*		* *	
Nd-YLF		* *	*	*			*	
Nd-Silica Glass		*	*	*			*	
Nd-Phosphate Glass		*	*	*			*	
Ti-Sapphire			*	****	**	****	*	
Cr-Alexandrite			***	*	*	*		
Cr-Ruby			*		*			

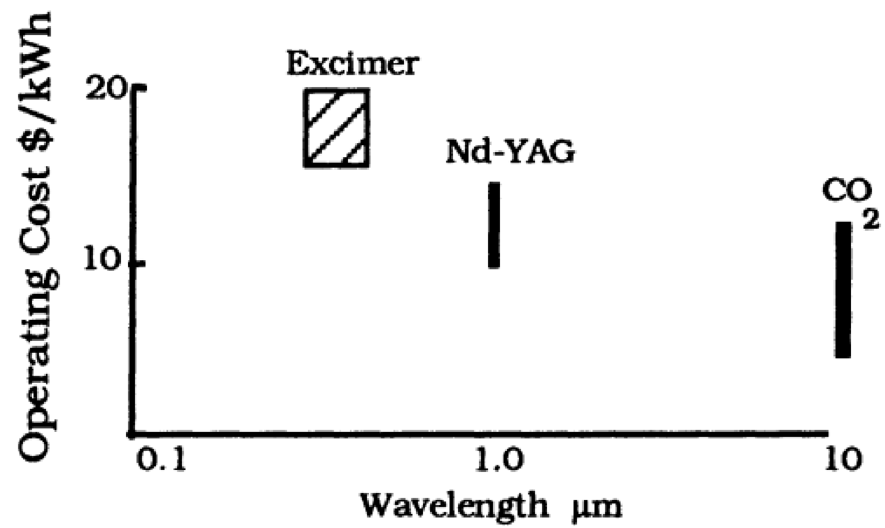
* approximate region of principle wavelengths.

Comparison Between Lasers -Power



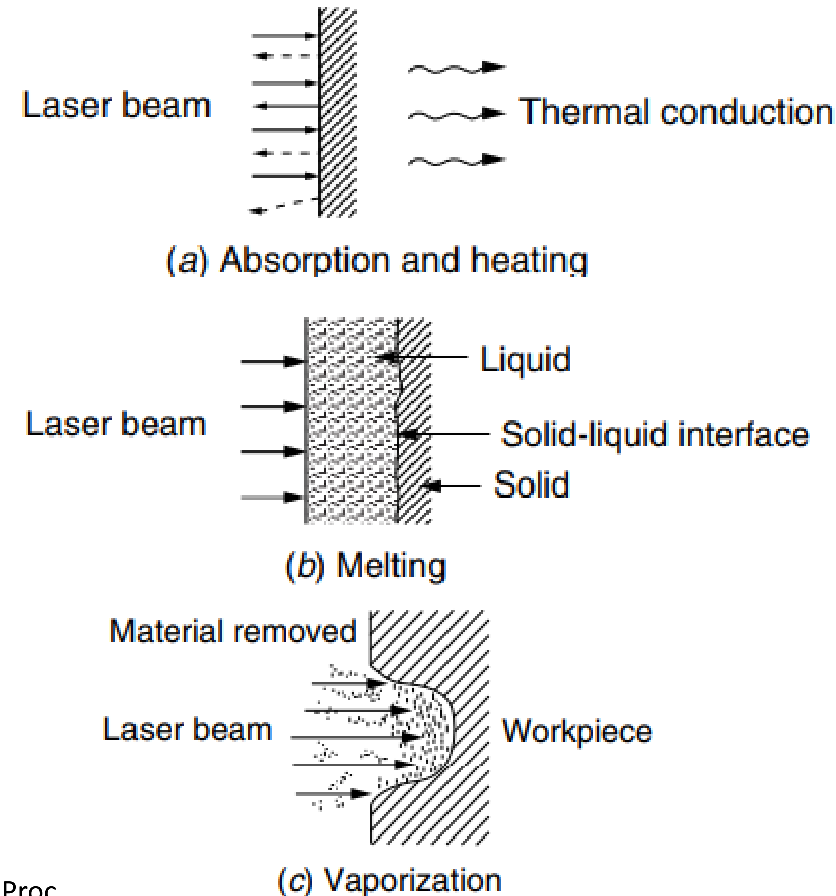
Cost Associated



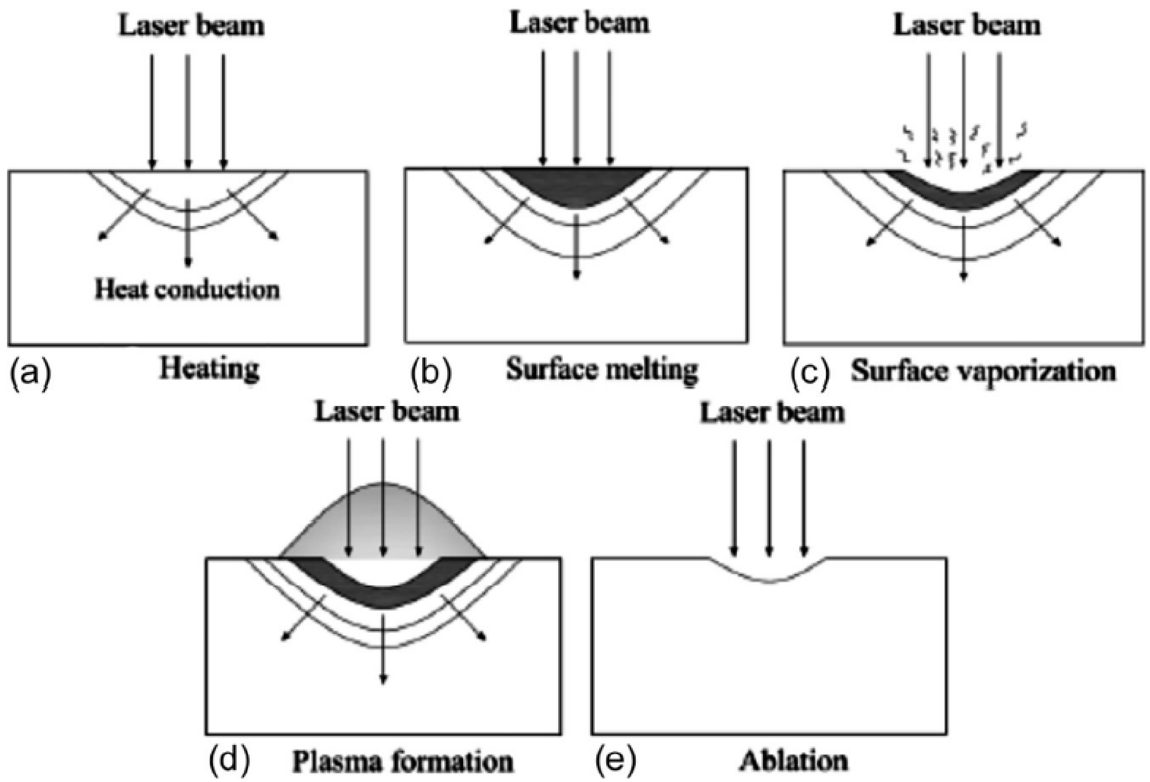


Material removal mechanism

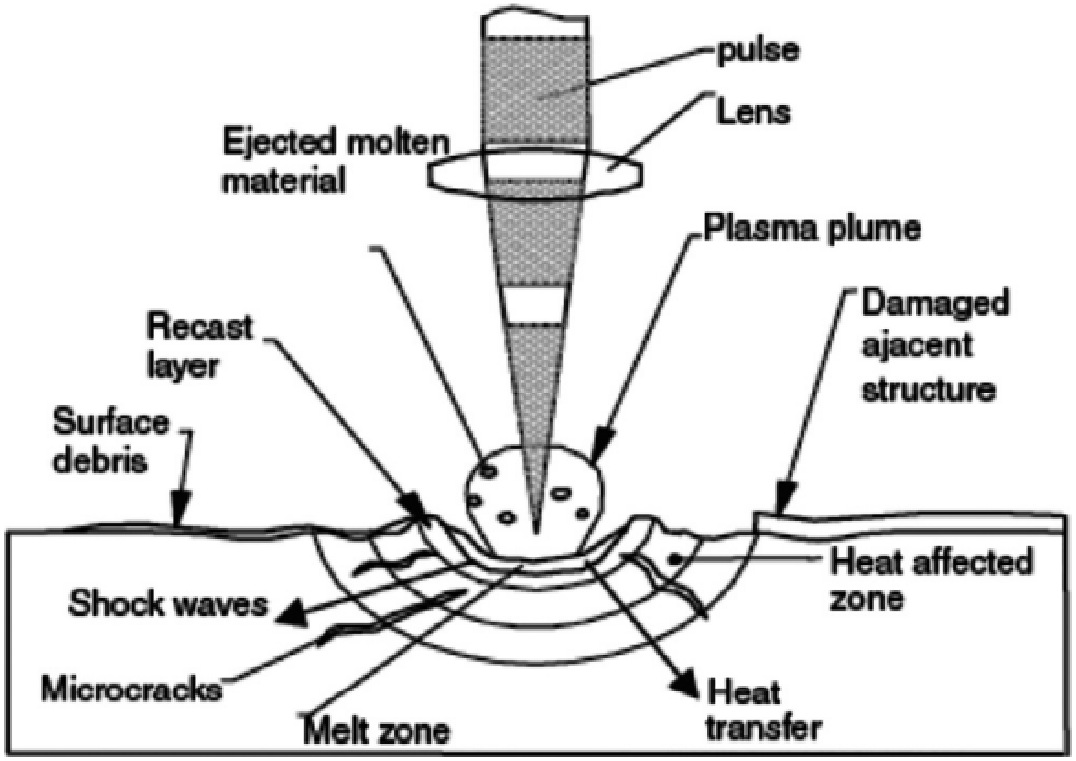
- The non-reflected light is absorbed, thus heating the surface of the specimen
- On sufficient heat the workpiece starts to melt and evaporates
- The physics of laser machining is very complex due mainly to scattering and reflection losses at the machined surface
- Additionally, heat diffusion into the bulk material causes phase change, melting, and/or vaporization
- Depending on the power density and time of beam interaction, the mechanism progresses from one of heat absorption and conduction to one of melting and then vaporization
- High intensity laser beams are not recommended since they form a plasma plume at or near the surface of the material with a consequent reduction in the process efficiency due to absorption and scattering losses.



Material Removal Mechanism



Material Removal Mechanism

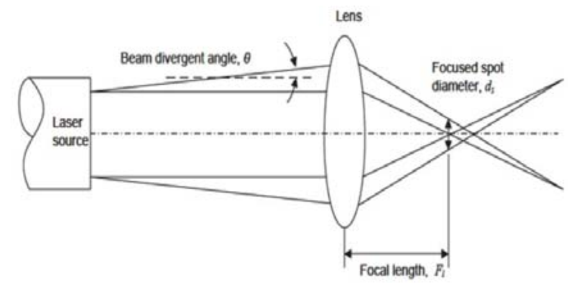


Material Removal Rate

- Machining by laser occurs when the power density of the beam is greater the energy lost by conduction, convection, and radiation, and moreover, the radiation must penetrate and be absorbed into the material.
- The power density of the laser beam, P_d, is given by

$$P_d = \frac{L_p}{A_b}$$

$$L_p = E_s/\Delta t \qquad\qquad A_b = \frac{\pi}{4}(d_s)^2$$



- The size of the spot diameter d_s is

$$d_s = F_l \alpha$$

where P_d = power density, W/cm^2 ; L_p = laser power, W; E_s = laser energy, J; F_l = focal length of lens, cm; Δt = pulse duration of laser, s; α = beam divergence, rad; d_s = spot size diameter, mm; A_b = area of laser beam at focal point, mm^2

Material Removal Rate

$$P_d = \frac{4L_p}{\pi F_l^2 \alpha^2}$$

- The machining rate ϕ (mm/min) can be described as follows:

$$\phi = \frac{C_l P_d}{E_v}$$

C_l = constant depending on the material and conversion efficiency;

E_v = vaporization energy of the material, J/mm^3;

Material Removal Rate

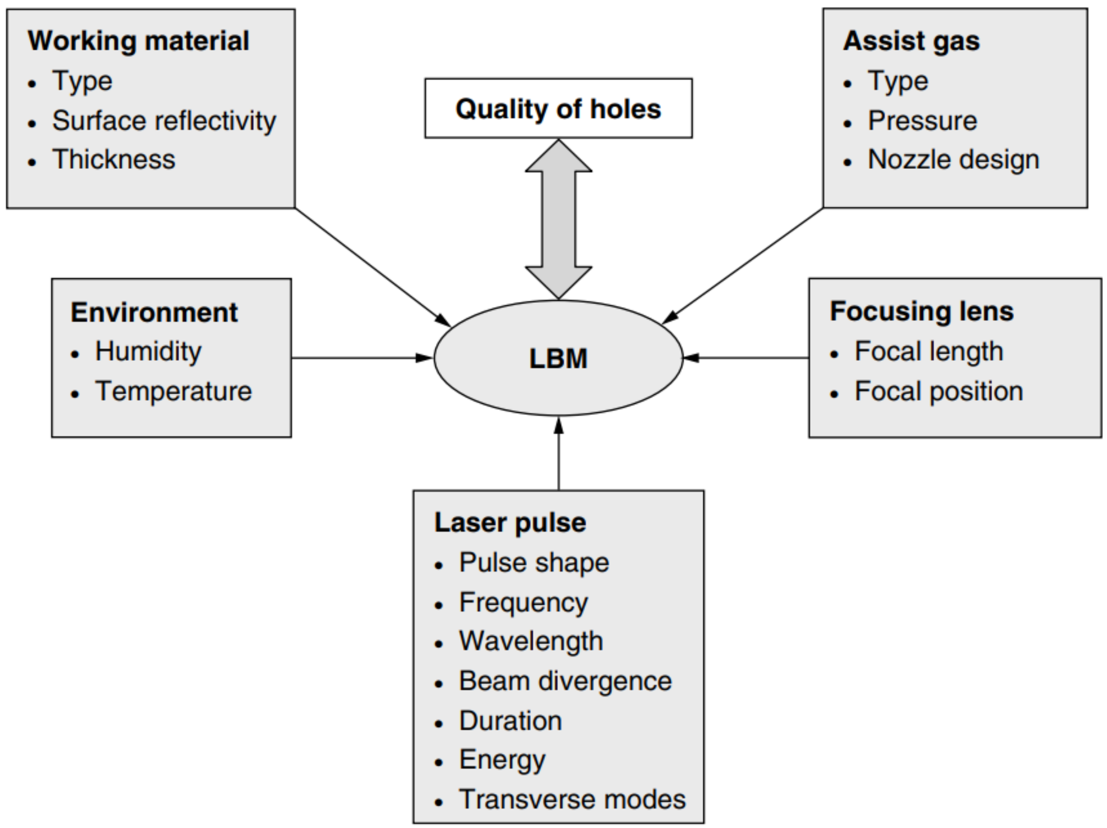
- The machining rate ϕ (mm/min) can be expressed as:

$$\phi = \frac{4C_l L_p}{\pi E_v F_l^2 \alpha^2}$$

- The volumetric removal rate (VRR) (mm^3 /min) can be calculated as follows:

$$VRR = \phi A_b = \frac{C_l L_p}{E_v}$$

Parameters


Working material
• Type
• Surface reflectivity
• Thickness
Quality of holes
Assist gas
• Type
• Pressure
• Nozzle design
Environment
• Humidity
• Temperature
LBM
Focusing lens
• Focal length
• Focal position
Laser pulse
• Pulse shape
• Frequency
• Wavelength
• Beam divergence
• Duration
• Energy
• Transverse modes

Advantages

- A wide variety of metallic and non-metallic materials can be machined
- No mechanical contact; therefore, no deformations of the workpiece and no tool wear are encountered
- Laser beam can travel without diffraction and can be branched to different work stations working at the same time
- It produces microholes in difficult-to-machine and refractory materials
- It is easy to control the beam characteristics to adapt the machining duty
- The process can be automated easily
- The operating cost is low
- It has a narrow heat-affected zone as compared to other thermal NTM process
- No cutting lubricants are required.

Disadvantages

- High equipment and maintenance cost
- Not safe in operation
- Blind holes of precise depth are difficult to achieve
- Laser produces tapered holes and hence limited thickness due to taper
- Holes produced are of limited dimensional and form accuracy, and of relatively bad surface quality
- HAZ cannot be avoided
- The process is of low efficiency and is not considered as a mass removal process compared to stamping
- Material thickness is restricted to 50 mm in the case of drilling
- Adherent materials at hole exits need to be removed
- Assist or cover gas is required