Laser Aided Manufacturing

Principles of Laser and Optics
Applications of Laser in Manufacturing Engineering
Laser Welding
Laser Surface Treatment
Laser Powder Deposition

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http://lorg.iut.ac.ir

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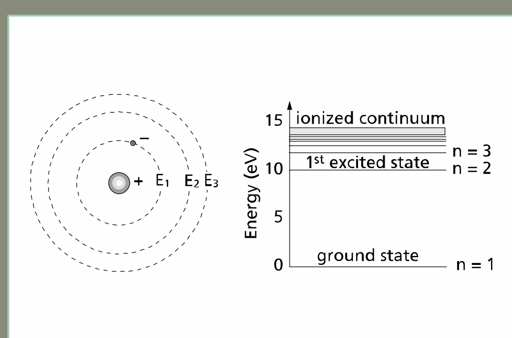
The Bohr Atom

In this model, electrons can go from one level to another level, but they cannot stay between them. That makes the "quantum energy states."

For an electron to jump to a higher quantum state, the atom must receive energy from the outside world. Likewise, when an electron drops from a higher state to a lower state, the atom must give off energy.



Bohr's atom and simple energy level diagram

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Photons and Energy

Photons are particles of zero mass. They have the characteristics of both wave and particle. Each photon has an intrinsic energy determined by the equation:

$$E = hn$$

There ν is the frequency of the light and *h* is Planck's constant. Since, for a wave, the frequency and wavelength are related by the equation:

$\lambda\nu$=c

where λ is the wavelength of the light and c is the speed of light in a vacuum. Therefore:

$$E = \frac{hc}{l}$$

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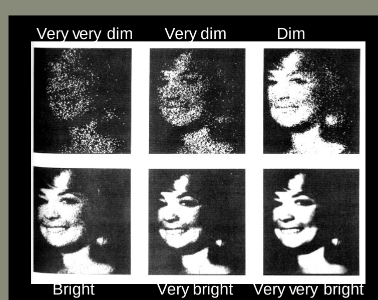
Light is not only a wave, but also a particle.

Photographs taken in dimmer light look grainier.



When we detect very weak light, we find that it's made up of particles. We call them photons.

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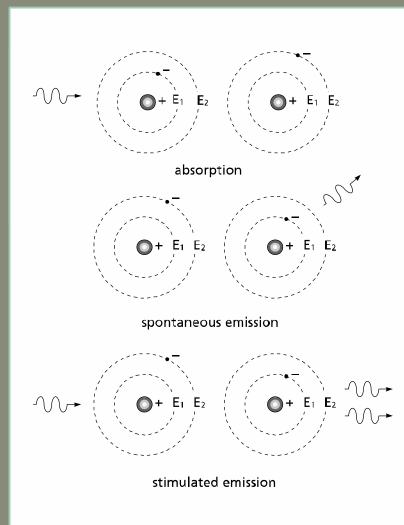
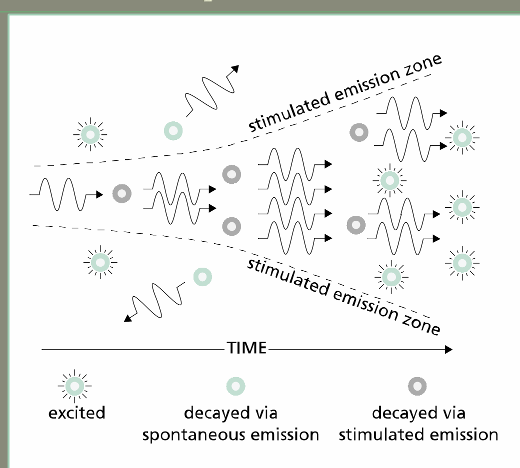
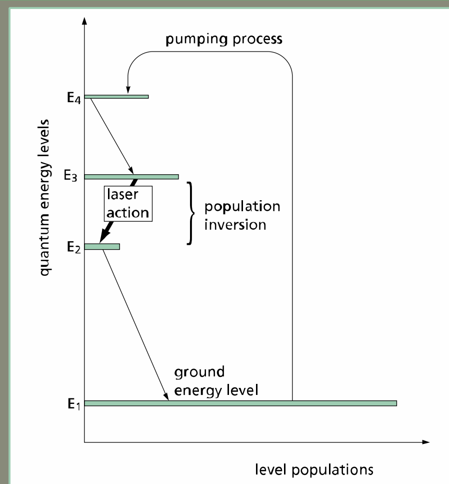
Spontaneous and stimulated emission



Amplification by stimulated emission



A four-level laser pumping system



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Laser Components

Lasing Medium:

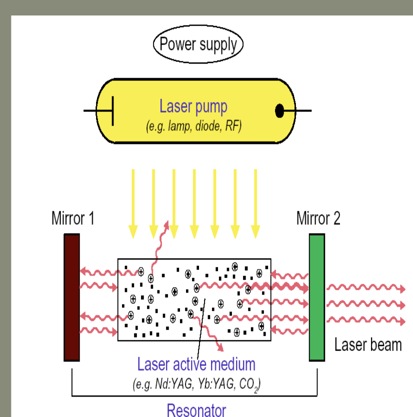
Provides appropriate **transition** and **Determines** the **wavelength**

Pump:

Provides energy necessary for **population inversion**

Optical Cavity:

Provides opportunity for **amplification** and **Produces** a **directional** beam (with defined length and transparency)



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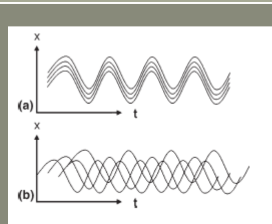
Properties of Laser beam

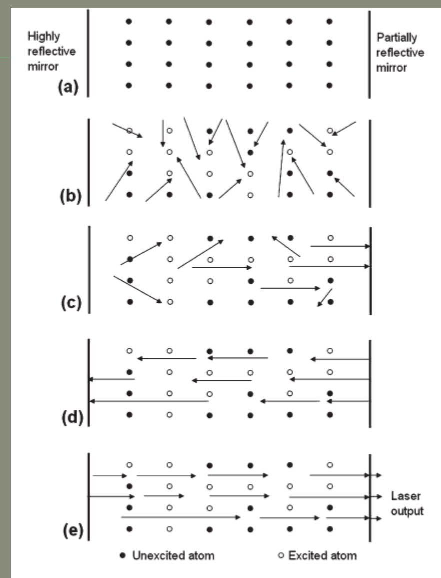
Coherent (synchronized phase of light)

Collimated (parallel nature of the beam)

Monochromatic (single wavelength)

High intensity (~10^{14} W / m^2)





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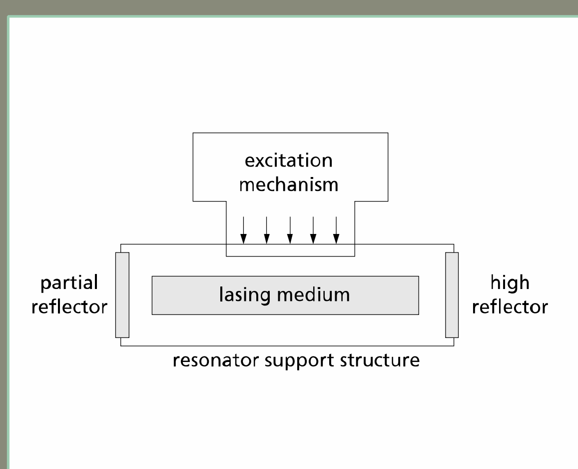
Schematic diagram of a basic laser



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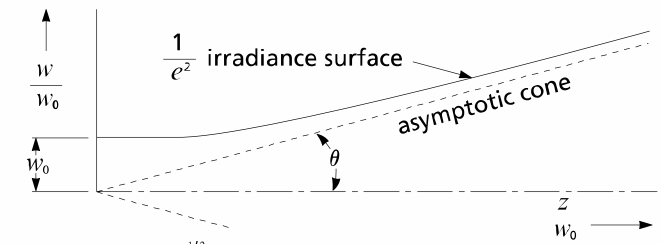
Propagation Characteristics of Laser Beams



$$w(z) = w_0\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2\right]^{1/2}$$

$$I(r) = I_0 e^{-2r^2/w^2} = \frac{2P}{\pi w^2} e^{-2r^2/w^2}$$

where z is the distance propagated from the plane where the wave- front is flat, λ is the wavelength of light, w_0 is the radius of the $1/e^2$ irradiance contour at the plane where the wavefront is flat, w(z) is the radius of the $1/e^2$ contour after the wave has propagated a distance z. I is the irradiance of the beam.

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LASER

Light Amplification by Stimulated Emission of Radiation

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List of Common Available Lasers

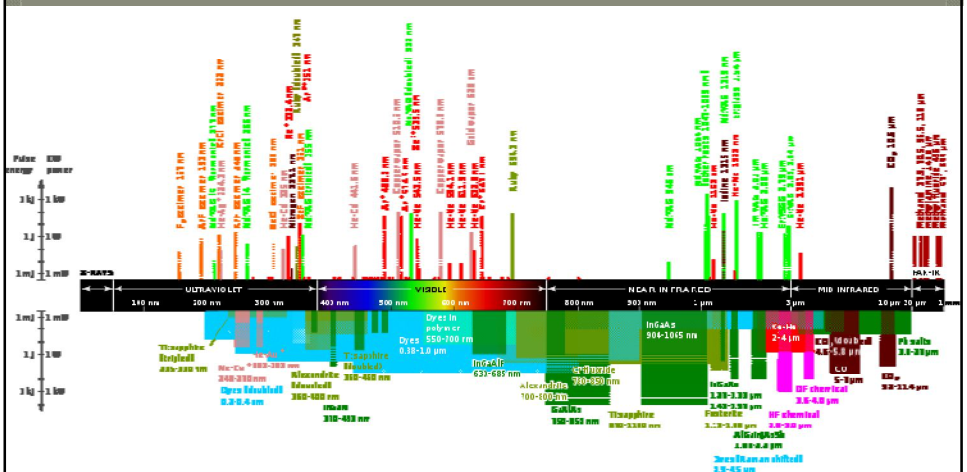

Table 0.1 Range of wavelengths for current commercial lasers

Laser type	Lasing species	Principle wavelength (μm)	Region	Date invented/commercialised
Excimer	F_2	0.157	UV	1975/1976
	ArF	0.193	UV	
	KrF	0.248	UV	
Nd:YAG frequency-quadrupled	$Nd^{3+} \times 4$	0.266	UV	
	XeCl	0.308	UV	
	XeF	0.351	UV	
Nitrogen	N_2	0.337	UV	1966/1969
AlGaN diode	Band gap	0.38–0.45 (tunable)	Blue	
Helium–cadmium	Cd^+	0.4416	Blue	1968/1970
Argon	Ar^+	0.4880	Blue	1964/1966
	Ar^+	0.5145	Green	
Copper vapour	Cu^*	0.5106	Blue-green	1966/1981
	Cu^*	0.5782	Yellow	
Nd:YAG frequency-doubled	$Nd^{3+} \times 2$	0.532	Green	
Helium–neon	Ne^*	0.6328	Red	1962
Ruby	Cr^{3+}	0.6943	Red	1960/1963
Alexandrite	Cr^{3+}	0.700–0.820 (tunable)	IR	1977/1981
Ti:sapphire	Ti^{3+}	0.670–1.100 (tunable)	IR	
AlGaAs diode	Band gap	0.7–0.9 (tunable)	IR	1962/1965
Nd:YAG or Nd:glass	Nd^{3+}	1.064	IR	1964/1966
Yb:YAG or Yb:glass	Yb^{3-}	1.030	IR	1990s
Chemical oxygen–iodine	Chemical ($O_2 + I_2$)	1.3	IR	1964/1983
Er:YAG	Er^{3+}	1.5	IR	
Hydrogen fluoride	Chemical ($H_2 + F_2$)	2.6–3.0	IR	1967/1977
Helium–neon	Ne^*	3.39	IR	
Carbon monoxide	CO vibration	5.4	IR	
Carbon dioxide	CO_2	9.4	IR	
	vibration	10.64	IR	1964/1966
Dye	Fluorescence	1.1–0.3 (tunable)	IR–UV	1962/1965
Free electron	Electron vibration	12.0–0.1 (tunable)	IR–UV	1963/1969

Table 0.2 Outline history of the development of the laser [5]

Date	Name	Achievement	References
1916	Albert Einstein	Theory of light emission. Concept of stimulated emission	[2, 3]
1928	Rudolph W. Ladenburg	Confirmed existence of stimulated emission and negative absorption	[17]
1940	Valentin A. Fabrikant	Noted possibility of population inversion	[18]
1947	Willis E. Lamb, R.C. Retherford	Induced emission suspected in hydrogen spectra. First demonstration of stimulated emission	[19]
1951	Charles H. Townes	The inventor of the maser at Columbia University. First device based on stimulated emission. Awarded the Nobel prize in physics in 1964	[20]
1951	Joseph Weber	Independent inventor of the maser at University of Maryland	[21]
1951	Alexander Prokhorov, Nikolai G. Basov	Independent inventors of the maser at Lebedev Laboratories, Moscow. Awarded the Nobel prize in physics in 1964	[22]
1954	Robert H. Dicke	"Optical bomb" patent based on pulsed population inversion for superradiance and a separate Fabry–Perot resonant chamber for a "molecular amplification and generation system"	[23]
1956	Nicolaas Bloembergen	First proposal for a three-level, solid-state maser at Harvard University	[24]
1957	Gordon Gould	First document defining a laser; notarised by a candy-store owner. Credited with patent rights in the 1970s	[25]
1958	Arthur L. Schawlow, Charles H. Townes	First detailed paper describing an "optical maser". Credited with the invention of the laser; from Columbia University	[26]
1960	Arthur L. Schawlow, Charles H. Townes	Laser patent no. 2,929,922	[27]
1960	Theodore Maiman	Invented the first working laser based on ruby, 16 May 1960. Hughes Research Laboratories	[1]
1960	Peter P. Sorokin, Mirek Stevenson	First uranium laser – second laser overall, November 1960. IBM Laboratories	[28]
1961	A.G. Fox, T. Li	Theoretical analysis of optical resonators at Bell Laboratories	[29]
1961	Ali Javan, William Bennett Jr., Donald Herriott	Invented the helium–neon laser at Bell Laboratories, Murray Hill, New Jersey	[30]
1962	Robert Hall	Invention of the semiconductor laser at General Electric Laboratory followed swiftly by others	[10]
1964	J.E. Geusic, H.M. Marcos, L.G. Van Uitert	Inventor of the first working Nd:YAG laser at Bell Laboratories	[8]
1964	Kumar N. Patel	Invention of the CO_2 laser at Bell Laboratories, Murray Hill, New Jersey	[7]
1964	William Bridges	Invention of the argon ion laser at Hughes Laboratories	[31]
1965	George Pimentel, J.V.V. Kasper	First chemical laser at University of California Berkley	[32]
1966	William Silvast, Grant Fowles, B.D. Hopkins	First metal vapour laser, Zn–Cd, at University of Utah	[33]

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Table 0.2 Outline history of the development of the laser [5]

Date	Name	Achievement	References
1966	Peter Sorokin, John Lankard	First dye laser action demonstrated at IBM Laboratories	[34]
1969	G.M. Delco	First industrial installation of three lasers for automobile application	(D. Roessler, private communication, 1995)
1970	Nicholai Basov's group	First excimer laser at Lebedev Laboratory, Moscow. Based on Xe only	[15]
1970	Zh.I. Alferov *et al.*	Invention of double heterostructure for laser diodes	[35]
1974	J.J. Ewing, Charles Brau	First inert gas halide excimer laser at AVCO Everet Laboratories	[14]
1977	John M.J. Madey's group	First free-electron laser at Stanford University	[16]
1980	Geoffrey Pert's group	First report of X-ray lasing action, Hull University, UK	[36]
1981	Arthur L. Schawlow, Nicholaas Bloembergen	Awarded the Nobel prize in physics for work in non-linear optics and spectroscopy	
1984	Dennis Matthews's group	First reported demonstration of a "laboratory" X-ray laser; from Lawrence Livermore National Laboratory	[37]
2000	Zh.I Alferov, H. Kroemer	Awarded the Nobel prize in physics for heterostucture invention	

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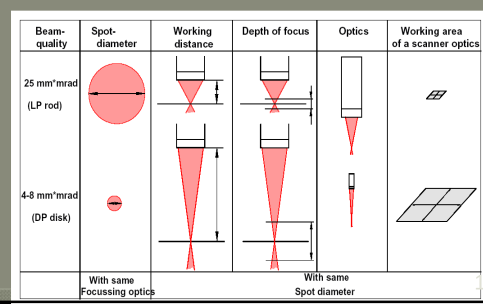
Laser Quality and Its Effect

Beam Quality

- ❖ A **measure** of Lasers' **capability** to be
  - ☺ **propagated** with low **divergence** and
  - ☺ **focused** to a small spot by a **lens** or **mirror**
- ❖ **Beam** Quality is measured by **M^2** or **BPP** (**B**eam **P**roduct **P**arameter, **mm.mrad**)
  - ✓ Ratio of **divergence** of **actual** beam to a **theoretical diffraction** limited beam with **same waist** diameter
  - ✓ **M^2= 1**; Ideal **Gaussian Beam**, perfectly diffraction limited
- ✓ **Value** of M^2 tends to **increase** with **increasing** laser **power**

Effects of Beam Quality



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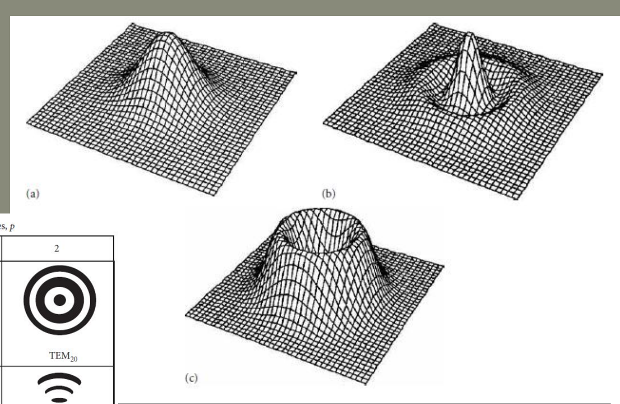
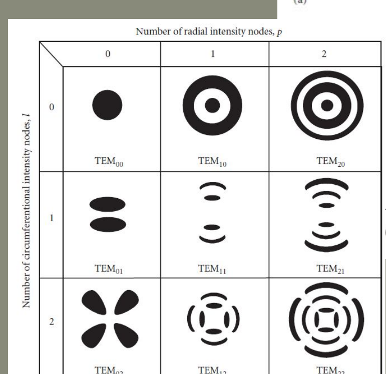
Spatial modes of laser beam



ensity distributions in cylindrical (a) TEM_{00}, (b) TEM_{10} and (c) annular (TEM_{01^*}) beam modes



The TEM is determined by:
the geometry of the cavity
the alignment and spacing of internal cavity optics; the gain distribution and propagation properties of the active medium;

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روش های رده بندی لیزرها

- حالت ماده موجود در محیط لیزری
  - گاز, مایع, جامد یا نیمه رسانا
- دمش و تحریک لیزر
  - تخلیه الکتریکی, درخشزن(دمش اپتیکی), کنش های شیمیایی
- ماهیت یا نحوه خروج انرژی
  - تپدار(پالس) یا موج پیوسته

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روش های رده بندی لیزرها (ادامه)

- مطابق با ناحیه گسیل طیفی لیزر
  - فروسرخ, مرئی, یا فرابنفش
- بر مبنای ترازهای انرژی برای ایجاد جمعیت معکوس
  - لیزرهای سه سطح و چهار سطح
- بر مبنای نحوه خنک کاری لیزر
  - هوا یا گاز (آزاد یا اجباری) و آب

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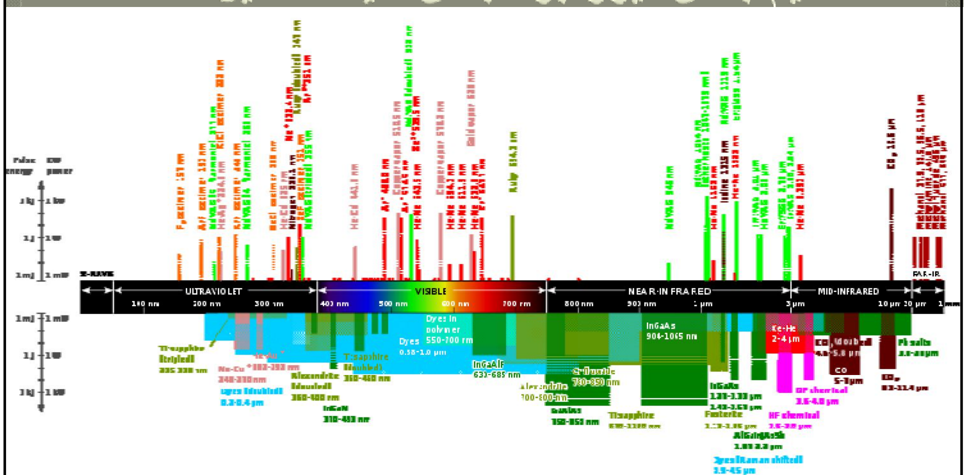
تقسیم بندی لیزر بر مبنای طیف گسیل



فرابنفش مرئی فروسرخ

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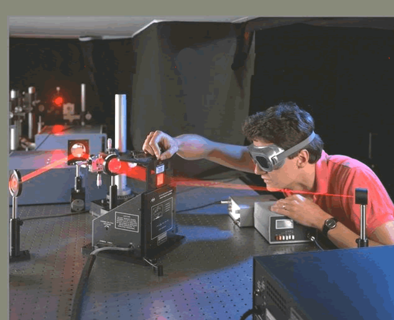
تقسیم بندی بر مبنای ترازهای انرژی برای ایجاد جمعیت معکوس



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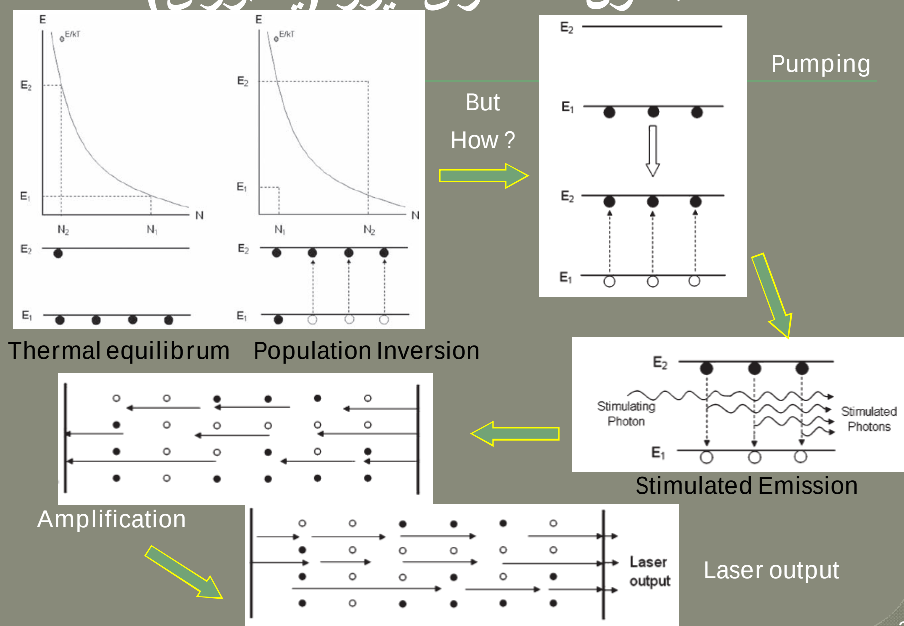
اصول عملگری لیزر (یادآوری)



ترازهای انرژی

Laser operation takes place via **transitions** between **diff**
molecular system

Rate equations for a two-level system

Rate equations for the densities of the two states:

Absorption, Stimulated emission, Spontaneous emission

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2$$

Pump intensity

$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2$$

If the total number of molecules is N:

$$N \equiv N_1 + N_2$$
$$\Delta N \equiv N_1 - N_2$$

$$\Rightarrow \frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2$$

$$2N_2 = (N_1 + N_2) - (N_1 - N_2) = N - \Delta N$$

$$\Rightarrow \frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

Credit: R. Trebino

$$\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

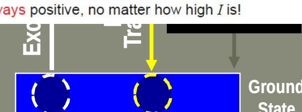
In steady-state: $0 = -2BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A + 2BI)\Delta N = AN$$
$$\Rightarrow \Delta N = AN/(A + 2BI)$$
$$\Rightarrow \Delta N = N/(1 + 2BI/A)$$
$$\Rightarrow \Delta N = \frac{N}{1 + I/I_{sat}}$$

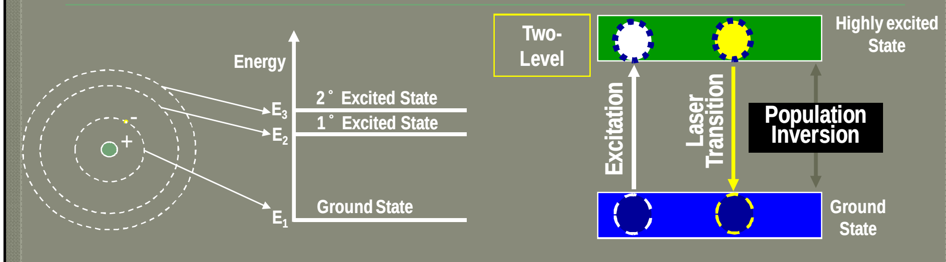
where: $I_{sat} = A/2B$

I_{sat} is the **saturation intensity**.

ΔN is always positive, no matter how high I is!



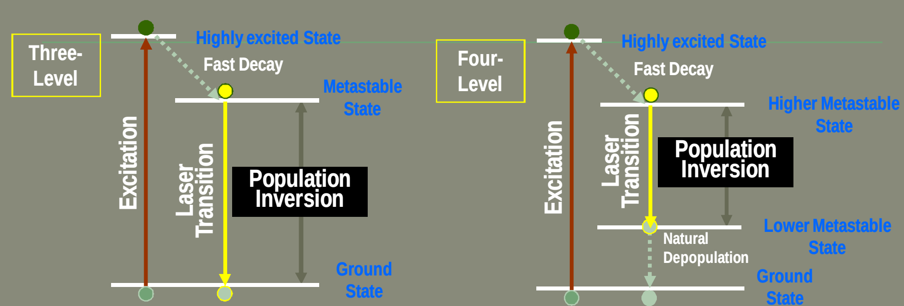
ترازهای انرژی



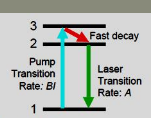
For material with Two-Level system
- ✓ Absorption and stimulated processes neutralize one another.
  - ❖ The material becomes transparent.

Population inversion is impossible

ترازهای انرژی



Population inversion, 3 level system



$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -BIN - BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A+BI)\Delta N = (A-BI)N$$

$$\Rightarrow \Delta N = N(A-BI)/(A+BI)$$

$$\Rightarrow \boxed{\Delta N = N\frac{1-I/I_{sat}}{1+I/I_{sat}}}$$

where: $I_{sat} = A/B$

I_{sat} is the **saturation intensity**.

Now if $I > I_{sat}$, ΔN is negative!

$$\boxed{\Delta N = -N\frac{I/I_{sat}}{1+I/I_{sat}}}$$

where: $I_{sat} = A/B$

I_{sat} is the **saturation intensity**.

Now, ΔN is negative—always!

Pulsed Laser

- Pulsed lasers are lasers which emit light not in a continuous mode, but rather in the form of optical pulses.

- The term is most commonly used for Q-switched lasers emitting nanosecond pulses

- Depending on the pulse duration, pulse energy, pulse repetition rate and wavelength required, very different methods for pulse generation and very different types of pulsed lasers are used

- For nanosecond pulse durations, various types of Q-switched lasers can be used. High pulse energies are achievable with solid-state bulk lasers. For small pulse energies, a microchip laser or a fiber laser can be suitable.

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List of Common Available Lasers

Table 1. Commercially available lasers and their industrial applications.

Laser	Year of discovery	Commercialised since	Application
Ruby	1960	1963	Metrology, medical applications, inorganic material processing
Nd-Glass	1961	1968	Length and velocity measurement
Diode	1962	1965	Semiconductor processing, biomedical applications, welding
He–Ne	1962		Light-pointers, length/velocity measurement, alignment devices
Carbon dioxide	1964	1966	Material processing-cutting/joining, atomic fusion
Nd-YAG	1964	1966	Material processing, joining, analytical technique
Argon ion	1964	1966	Powerful light, medical applications
Dye	1966	1969	Pollution detection, isotope separation
Copper	1966	1989	Isotope separation
Excimer	1975	1976	Medical application, material processing, colouring

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Types of Laser based on state of active medium used

- Gas Laser: He-Ne, Argon ion and CO_2
- Solid state Laser : Ruby, Nd:YAG, Nd:glass
- Semiconductor Laser
- Tunable dye Laser

لیزرهای گازی

- ماده فعال کننده یک گاز
- جمعیت معکوس بسیار کمتر از جامدات:
- لیزرهای گازی پرقدرت بسیار حجیم و بزرگ
- تحریک توسط تخلیه الکتریکی
- انواع لیزر گازی:
  - لیزر اتمی نظیر هلیوم-نئون, بخار مس
  - لیزرهای یونی نظیر آرگون, هلیم-کادمیم
  - لیزرهای مولکولی نظیر دی اکسید کربن, لیزر ازت و اگزیمر

He-Ne laser

•Laser medium is mixture of Helium and Neon gases in the ratio 10:1
•Medium excited by large electric discharge, flash pump or continuous high power pump
•In gas, atoms characterized by sharp energy levels compared to solids
•Actual lasing atoms are the Neon atoms

Pumping action:
Electric discharge is passed through the gas
Electrons are accelerated, collide with He and He atoms and excite them to higher energy levels

The CO2 LASER:

•Lasers discussed above – use transitions among various excited electronic states of an atom or ion
•CO2 laser – uses transition between different vibrational states of CO2 molecule
•One of the earliest Gas lasers
•Highest power continuous wave laser currently available
•The filling gas within the discharge tube consists primarily of:

Carbon dioxide
Hydrogen
Nitrogen
Helium
(proportions vary according to a specific laser)

لیزر حالت جامد

- در این نوع لیزر ، ماده فعال ایجاد کننده لیزر ، یک یون فلزی است که با غلظت کم در شبکه یک بلور یا درون شیشه ، به صورت ناخالصی قرار داده شده است. فلزاتی که برای این منظور بکار می‌روند عبارتند از :

- اولین سری فلزات واسطه
  - لانتانیدها
  - آکتینیدها

- ازمهمترین لیزرهای حالت جامد می‌توان از لیزر یاقوت که یک لیزر سه ترازی است و لیزرهای نئودنیوم Nd:YAG , d:glass می‌توان نام برد.

لیزر یاقوت
RUBY LASER

- First laser to be operated successfully
- Lasing medium: Matrix of Aluminum oxide doped with chromium ions
- Energy levels of the chromium ions take part in lasing action
- A three level laser system

<u>Working:</u>

Ruby is pumped optically by an intense flash lamp

This causes Chromium ions to be excited by absorption of Radiation around 0.55 μm and 0.40μm

***Semiconductor Lasers* لیزر نیمه هادی**

- Use semiconductors as the lasing medium

Advantages:

- Capability of direct modulation into Gigahertz region
- Small size and low cost
- Capability of Monolithic integration with electronic circuitry
- Direct Pumping with electronic circuitry
- Compatibility with optical fibers

❖Basic mechanism of light emission from a semiconductor
❖Homojunction and Heterojunction lasers
❖Threshold current density
❖Carrier and Photon confinement

✓Most SC lasers operate in 0.8 – 0.9 μm or 1 – 1.7 μm spectral region
✓Wavelength of emission determined by the bandgap
✓Different SC materials used for different spectral regions
✓0.8 – 0.9 μm : Based on Gallium Arsenide
✓1 – 1.7 μm : Based on Indium Phosphide (InP)

Laser Parameters for several common lasers

Gain medium	Pump type	Wavelength	Power/Energy	Output type	Beam diameter	Beam divergence	Efficiency	Cooling
Gas, atomic								
Helium Neon	electric discharge	0.6328 μm, others	0.1–50 mW	cw	0.5–2.5 mm	0.5–3 mrad	<0.1%	air
Helium Cadmium	electric discharge	325 nm, 441.6 nm, others	5–150 mW	cw	0.2–2 mm	1–3 mrad	<0.1%	air
Gas, ion								
Argon	electric discharge	several from 350–530 nm, main lines: 488 nm, 514.5 nm	2 mW–20 W	cw (or mode-locked)	0.6–2 mm	0.4–1.5 mrad	<0.1%	water or forced air
Krypton	electric discharge	several from 350–800 nm, main line: 647.1 nm	5 mW–6 W	cw (or mode-locked)	0.6–2 mm	0.4–1.5 mrad	<0.05%	water or forced air
Gas, molecular								
Carbon Dioxide	electric discharge	10.6 μm	3 W–20 kW	cw or long pulse	3–50 mm	1–3 mrad	5–15%	flowing gas
Nitrogen	electric discharge	337.1 nm	1–300 mW (average)	pulsed	2 × 3–6 × 30 mm (rectangular)	1–3 × 7 mrad	<0.1%	flowing gas
Gas, excimer								
Argon Fluoride	short-pulse electric discharge	193 nm	up to 50 W (average)	pulsed	2 × 4–25 × 30 mm (rectangular)	2–6 mrad	<1%	air or water
Krypton Fluoride	short-pulse electric discharge	248 nm	up to 100 W (average)	pulsed	2 × 4–25 × 30 mm (rectangular)	2–6 mrad	<2%	air or water
Xenon Chloride	short-pulse electric discharge	308 nm	up to 150 W (average)	pulsed	2 × 4–25 × 30 mm (rectangular)	2–6 mrad	<2.5%	air or water
Xenon Fluoride	short-pulse electric	351 nm	up to 30 W (average)	pulsed	2 × 4–25 × 30 mm (rectangular)	2–6 mrad	<2%	air or water

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Laser Parameters for several common lasers

Gain medium	Pump type	Wavelength	Power/Energy	Output type	Beam diameter	Beam divergence	Efficiency	Cooling
Liquid								
Various Dyes	other lasers, flashlamp	tunable 300–1000 nm	20 mW–1W (average)	cw or (ultrashort) pulsed	1–20 mm	0.3–2 mrad	1–20%	dye flow or water
Solid-State								
Nd:YAG	flashlamp, arc lamp, diode laser	1.064 μm	up to 10 kW (average)	cw or pulsed	0.7–10 mm	0.3–25 mrad	0.1–2% (5–8%, diode pumped)	air or water
Nd:glass	flashlamp	1.06 μm	0.1–100 J per pulse	pulsed	3–25 mm	3–10 mrad	1–5%	water
Alexandrite	flashlamp	tunable, 700–818 nm	<100 W average power	cw or pulsed	a few mm	a few mrad	0.5%	air or water
Ti-sapphire	flashlamp, diode laser, doubled Nd:YAG	tunable, 660–1000 nm	~2 W average power	cw or (ultrashort) pulsed	a few mm	a few mrad	comparable to Nd:YAG	air or water
Erbium:Fiber	flashlamp, diode laser	1.55 μm	1–100 W	cw or pulsed	a few mm	a few mrad	comparable to Nd:YAG	air
Semiconductor Lasers								
GaAs, GaAlAs	electric current, optical pumping	780–900 nm, composition dependent	1 mW to several watts, diode arrays up to 100 kW	cw or pulsed	N/A (diverges too rapidly)	200 × 600 mrad (oval in shape)	1–50%	air, heat sink
InGaAsP	electric current, optical pumping	1100–1600 nm, composition dependent	1 mW to ~1 W	cw or pulsed	N/A (diverges too rapidly)	200 × 600 mrad (oval in shape)	1–20%	air, heat sink

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Laser types

❖ Typical commercial lasers used for laser material processing

1. **CO_2** Laser
2. **Nd^{3+}:YAG** Lasers
   - ✓**Lamp-**pumped
   - ✓**LD-**pumped
3. **Disk** Laser
4. **Diode** Laser
5. **Fiber** Laser

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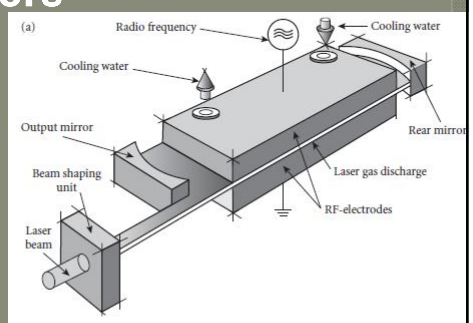
CO_2 Lasers

CO_2 Laser: Characteristics	
Wavelength	10.6 μm; far-infrared ray
Laser Media	CO_2–N_2–He mixed gas (gas)
Average Power (CW)	45 kW (maximum) (Normal) 500 W – 10 kW
Merits	Easier high power (efficiency: 10–20%)



CO_2 Laser: M^2 values [CW]

Output power (W)	M^2
<500	1.1-1.2
800-1000	1.2-2
1000-2500	1.2-3
5000	2-5
10,000	10

CO_2 Laser: Application	
Automobile Industries	2.5 to 7 kW class (Alder, 2003)
Steel and Shipbuilding Industries	5 to 45 kW(Minamida, 2002)

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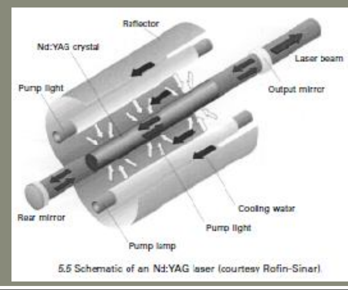
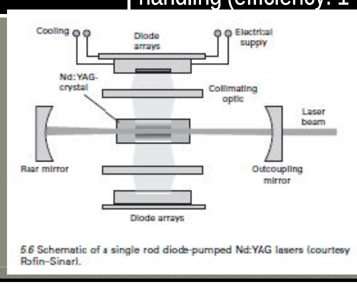
YAG Laser

Lamp-pumped YAG Laser: Characteristics	
Wavelength	1.06 μm; near-infrared ray
Laser Media	Nd^{3+}: $Y_3Al_5O_{12}$ garnet (solid)
Average Power [CW]	10 kW (cascade type & fiber-coupling) (Normal) 50 W–4 kW
Merits	Fiber-delivery, and easier handling (efficiency: 1–4%)



5.5 Schematic of an Nd:YAG laser (courtesy Rofin-Sinar).



5.6 Schematic of a single rod diode-pumped Nd:YAG lasers (courtesy Rofin-Sinar).

LD-pumped YAG Laser: Characteristics	
Wavelength	about 1 μm; near-infrared ray
Laser Media	Nd^{3+} : $Y_3Al_5O_{12}$ garnet (solid)
Average Power	[CW] : 13.5 kW (fiber-coupling max.) [PW] : 6 kW (slab type max.)
Merits	Fiber-delivery, high brightness, and high efficiency (10–20%)

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YAG Laser

YAG Laser: M^2 values [CW & PW]	
Output power (W)	**M^2**
0-20	1.1-5
20-50	20-50
50-150	50-75
150-500	75-150
500-4000	75-150

YAG Laser Application: Automobile Industries	
Lamp-pumped	3 to 4.5 kW class; SI fiber delivered **(Mori, 2003)**
LD-pumped	2.5 to 6 kW
New Development	**Rod-type:** 8 and 10 kW; Laboratory Prototype
	Slab-type: 6 kW; Developed by Precision Laser Machining Consortium, PLM

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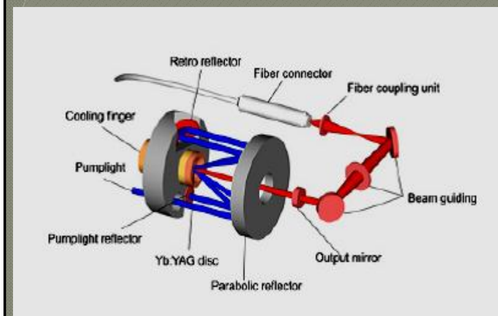
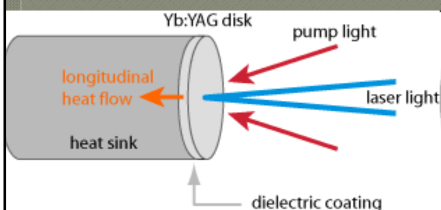
Disk Laser



Disk Laser: Characteristics	
Wavelength	1.03 μm; near-infrared ray
Laser Media	Yb^{3+} : YAG or YVO_4 (solid)
Average Power	6 kW (cascade type max.)
Merits	Fiber-delivery, high brightness, high efficiency(10–15%)



Commercially available **disk** laser system: 1 and **4** kW class

- ❖ Beam **delivery** with **150** and **200** μm diameter **fiber**
- ❖ **Even** a **1 kW** class laser is **able** to produce
  - ✓a **deep keyhole-type** weld bead
  - ✓**extremely** narrow width in **stainless** steel and **aluminum** alloy

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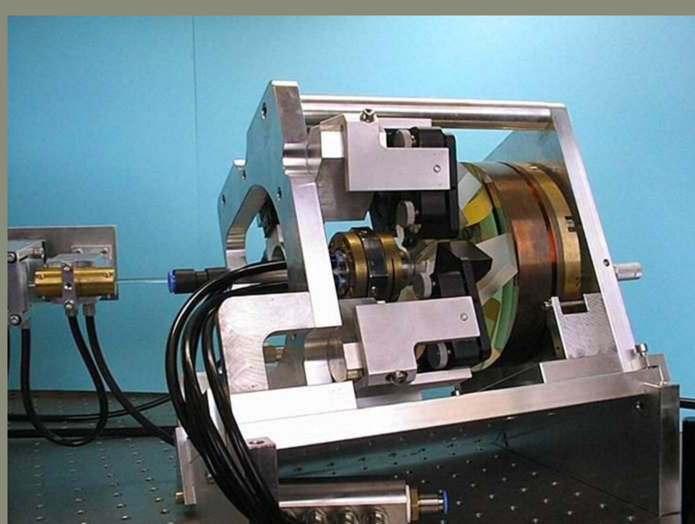
Disk Laser



Source Trumpf

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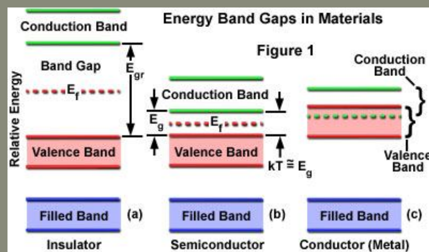
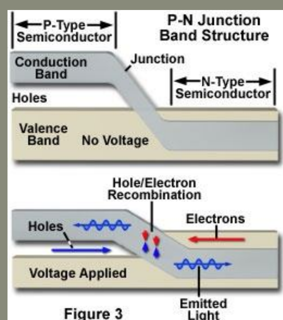
Diode Laser



Diode Laser: Characteristics	
Wavelength	0.8–0.95 mm; near-infrared ray
Laser Media	InGaAsP, etc. (solid)
Average Power [CW]	10 kW (stack type max.) 5 kW (fiber-delivery max.)
Merits	Compact, and high efficiency (20–50%)



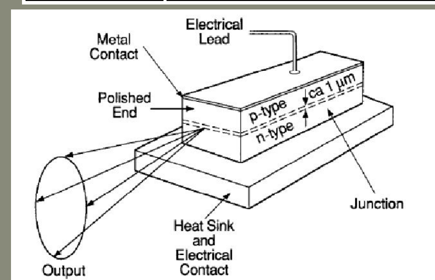


Figure 3-18 A simple semiconductor laser structure.

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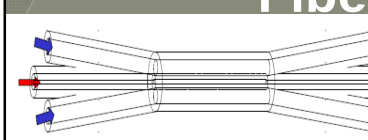
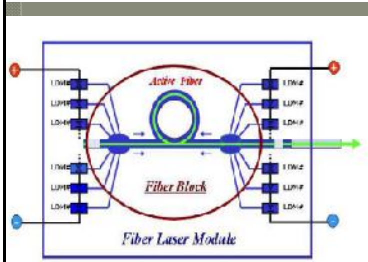
Fiber Laser





Fiber Laser: Characteristics	
Wavelength	1.07 μm; near-infrared ray
Laser Media	Yb^{3+} : SiO_2 (solid), etc.
Average Power [CW]	20 kW (fiber-coupling max.)
Merits	Fiber-delivery, high brightness, high efficiency(10–25%)

Recent Development

- ❖ **Fiber** lasers of **10kW** or **more** are **commercially** available
- ❖ Fiber lasers of **100kW** and **more** are **scheduled**
- ❖ **Fiber** laser at **6.9kW** is able to provide **deeply penetrated** weld at **high** speed
- ❖ **Fiber** laser is able to **replace** high quality (slab) **CO_2 laser** for **remote** or **scanning** welding

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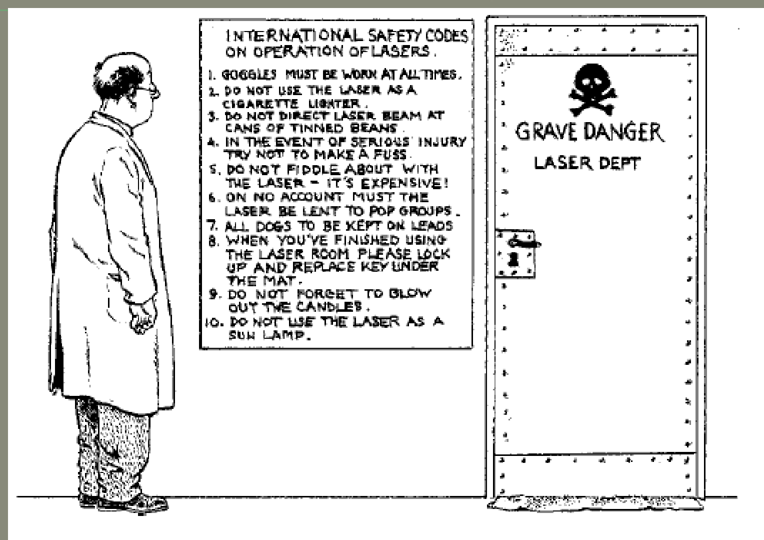
Any Question?



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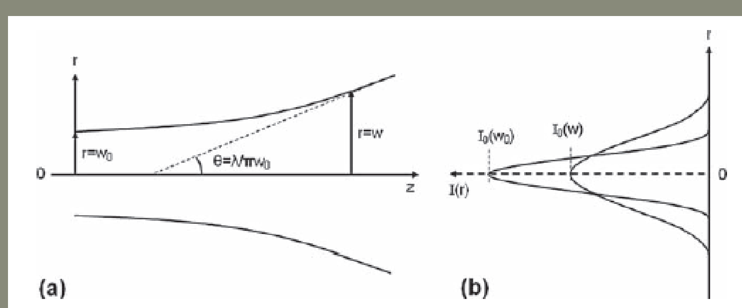
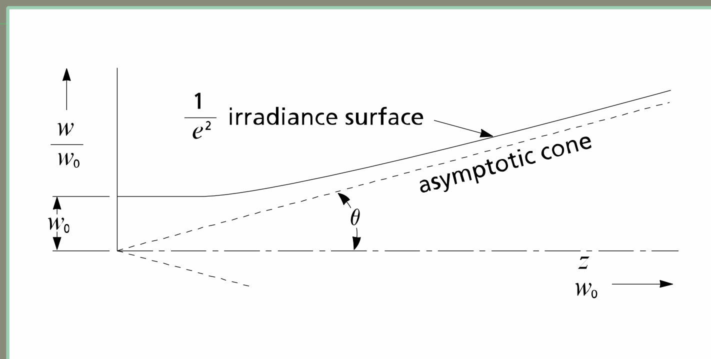
Propagation of a Gaussian laser beam

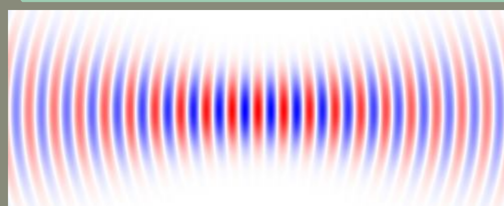


$$I(r) = I_0 \exp\left(-2\frac{r^2}{r_0^2}\right)$$

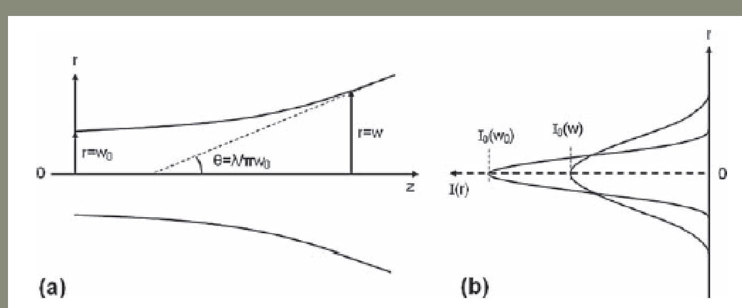
$$d(z) = d_0\sqrt{1 + \left(\frac{4\lambda z}{\pi d_0^2}\right)^2}$$

Propagation Characteristics of Laser Beams





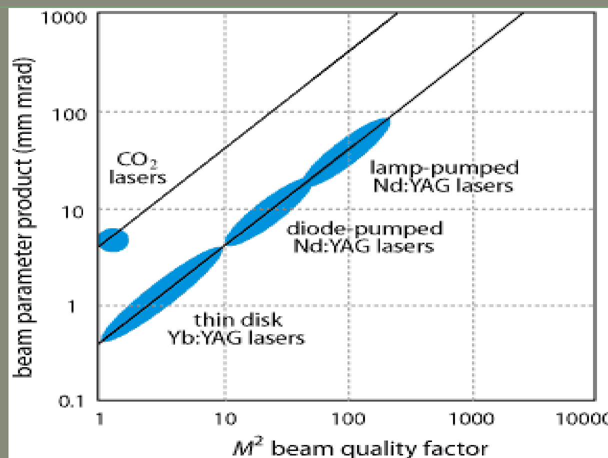
Propagation of a Gaussian laser beam



$$I(r) = I_0 \exp\left(-2\,\frac{r^2}{r_0^2}\right)$$

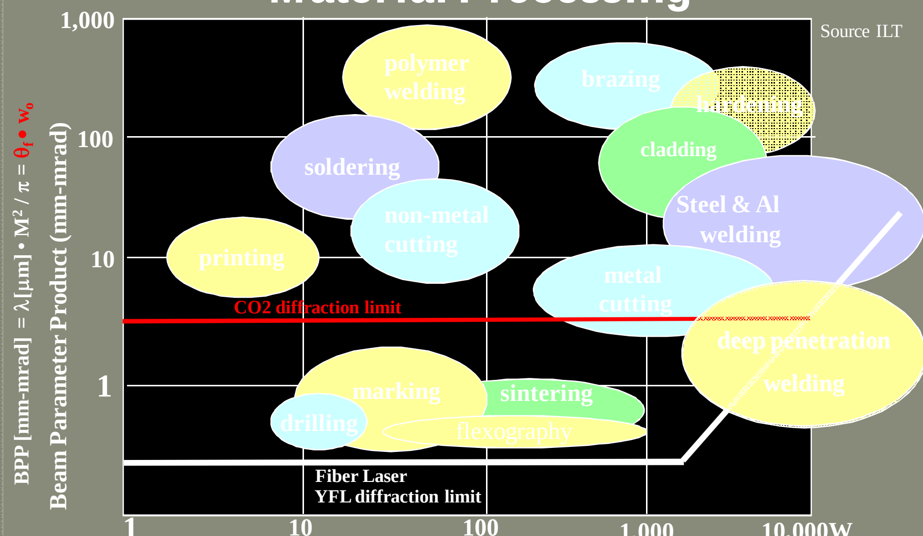
$$d(z) = d_0\sqrt{1+\left(\frac{4\lambda z}{\pi d_0^2}\right)^2}$$

Beam parameter product

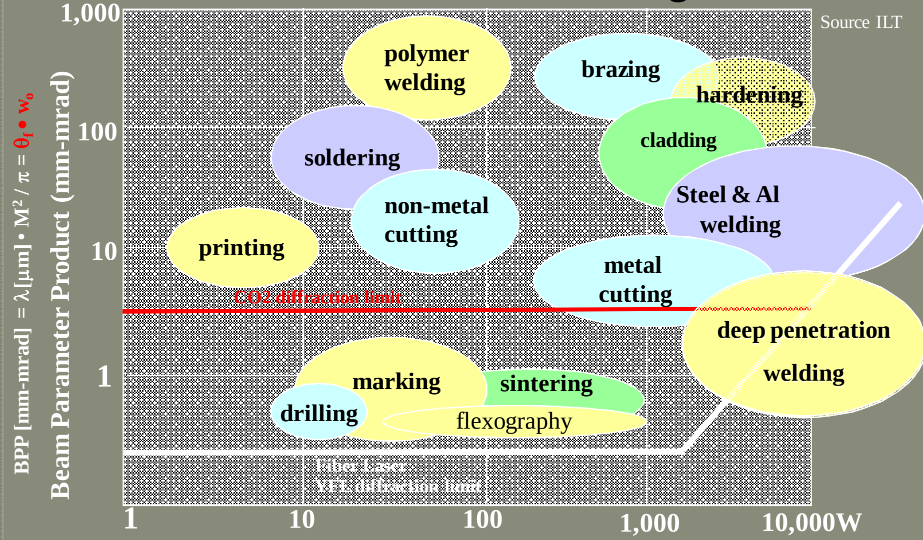


BPP: product of the beam radius in a focus and the far-field beam divergence

Application Domains of Laser Material Processing



Application Domains of Laser Material Processing



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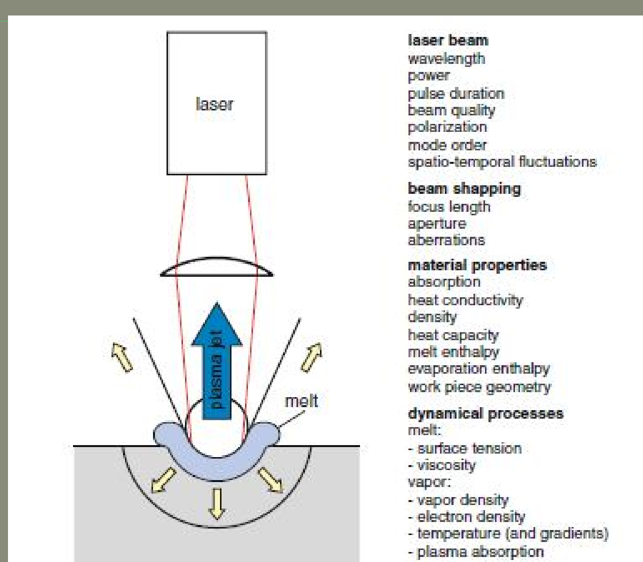
Effective Parameters In Laser Material Processing



From R. wester

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Laser Processing Applications

Laser Marking
Laser Cutting
Laser Drilling
Laser Surface Treatment
Laser Cladding
Direct Laser Fabrication
Laser Forming
Laser Welding

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Laser Marking

- **The worlds largest laser application**
- **Relevant to all sectors**
- **Almost any material can be marked with laser**

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Laser Cutting

- Application to a wide range of materials and thickness
- Narrow kerf widths
- High speeds
- Very high repeatability
- Very high reliability
- Easily automated and programmable
- Flexibility in changeovers
- Reduced tooling costs and setup times
- Non-contact process
- Versatility (same tool for welding)
- 3D cutting
- Cloths and plastic cutting

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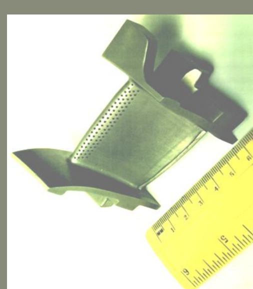
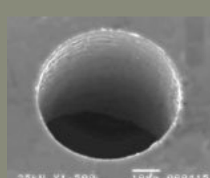
Laser Drilling

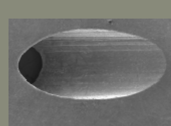
Material Removal Process

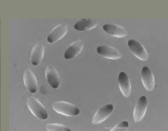


- Hole diameters dependent on laser source
- Trepanning: small / large holes > 0.6mm
- Precision: small holes < 0.6mm
- Advantages of Trepanning
- Shaped holes
- Advantages of Percussion
- Drilling on the fly



50 μm diameter hole in steel





Laser drilled injector holes, 60 Deg

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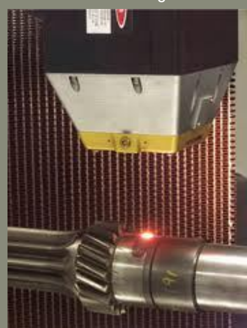
Laser Surface Treatment

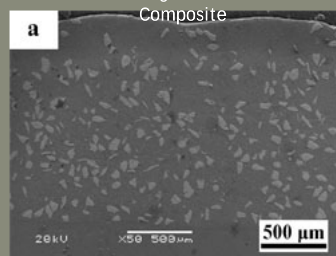
Three main processes: hardening, melting, cladding

Laser Transformation Hardening



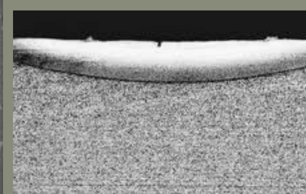
http://www.laser-industrial.com/

Laser Cladding of Metal-Ceramic Composite



English.cas.cn

Laser Surface Melting



http://www.gsiglasers.com/

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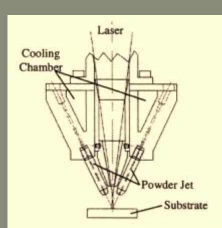
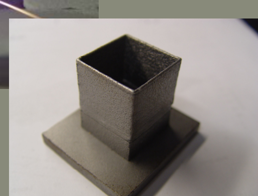
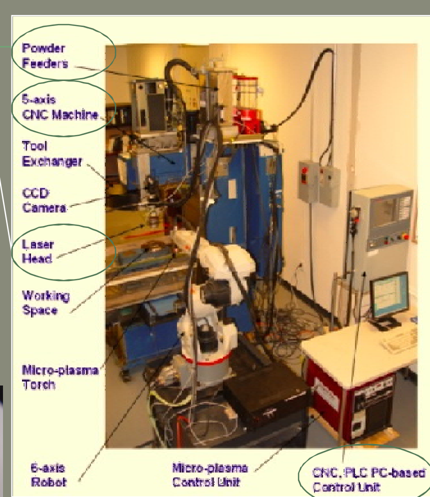
Direct Laser Fabrication







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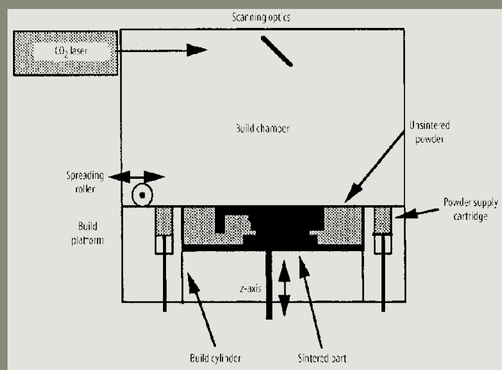
Selective Laser Sintering

- Parts built up layer by layer
- A laser beam selectively melts powder into a designated shape
- The component sinks into the bed, a layer of powder is deposition above the component
- The process repeats until the component is finished



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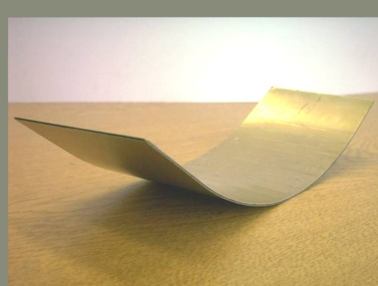
Laser Forming

- Bending metal with light
- Laser beam induces thermal stresses
- The plate expands, cools and contracts
- The flat plate deforms into a new shape



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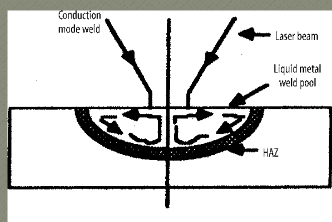
Laser Welding

Laser Welding Modes

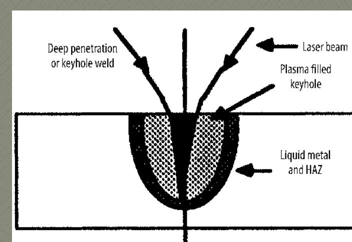
- Conduction Welding
- Deep Penetration Welding (Keyhole Welding)

Conduction Welding: the power density is insufficient to cause boiling and therefore generate a keyhole. The weld pool has strong stirring forces driven by Marangoni-type forces resulting from the variation in surface tension with temperature.

Keyhole Welding: there is sufficient energy to cause evaporation and hence a hole in the melt pool. This hole is stabilized by the pressure from the vapour being generated. The "keyhole" behaves like an optical black body, it enables the beam to be nearly all absorbed.



Conduction-limited weld



Keyhole type weld

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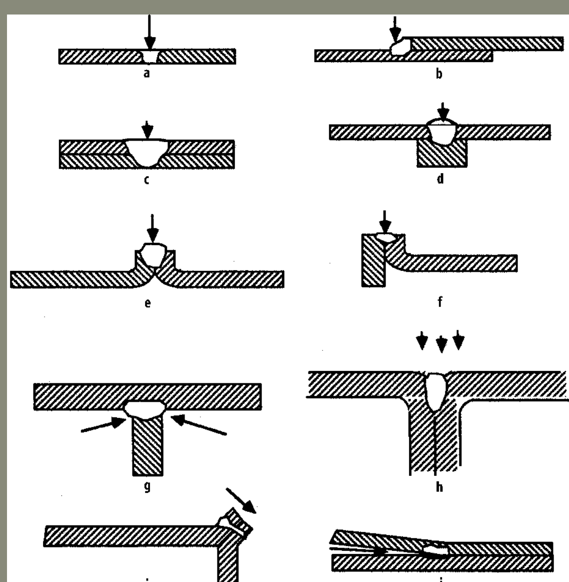
Joint Arrangements



Various welding joint arrangements: a butt joint, b fillet or lap joint, c spot or lap weld, d spike or spot weld, e flange joint, f edge joint, g T-joint, h flare weld, i corner, and j kissing or flare weld

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LASER SAFETY

ايمني درليزر

كارگاه آموزشي مقدمات اصول ليزر
23 آبان 1391
دانشكده مهندسي مكانيك

The Dangers

All energy is dangerous, even gaining potential energy walking up stairs is dangerous!

The laser is no exception,
but it poses an unfamiliar hazard in the form of an optical beam

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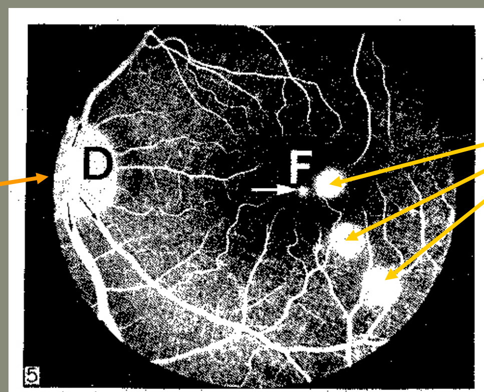
We don't want this!

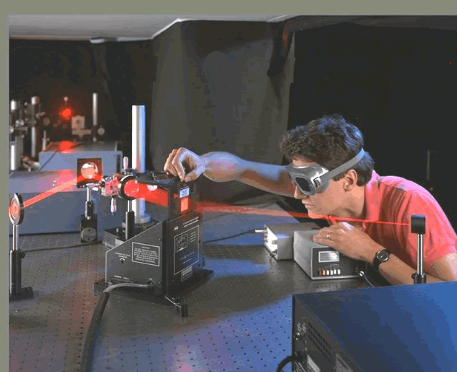
Optic nerve



lesions

Fluorescein angiograph of retina after laser irradiation

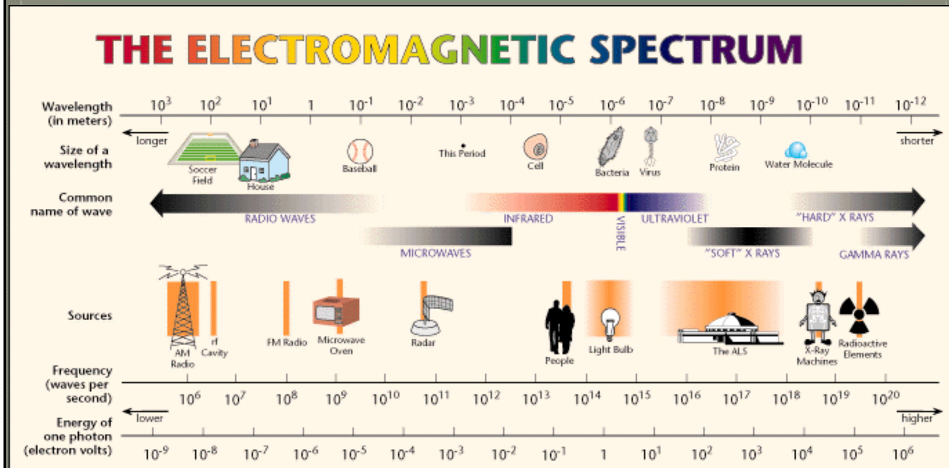
Welcome to Laser Safety Training



Instruction is mandatory!

Training is essential for your safety!

The electromagnetic spectrum



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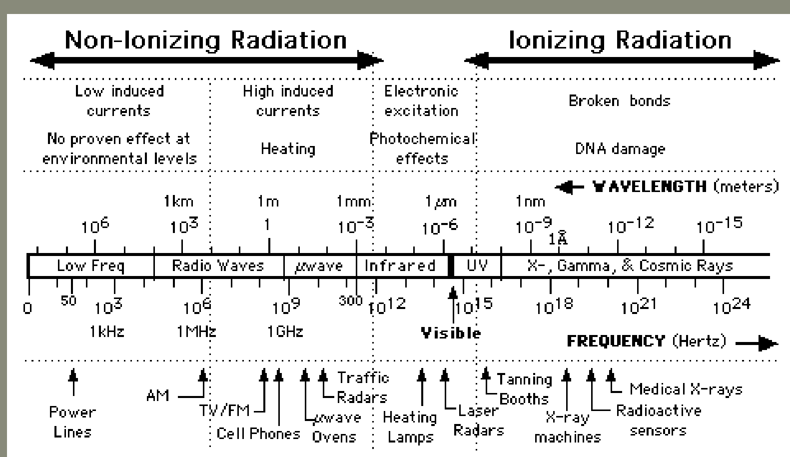
The electromagnetic spectrum



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Wavelengths Magnitudes

Ultraviolet radiation sub-divided ranges:

- UV – A 315 nm to 400 nm
- UV – B 280 nm to 315 nm
- UV – C 100 nm to 280 nm

Visible region: between 400 nm and 780 nm

Infrared radiation sub-divided ranges:

- IR - A 780nm to 1400 nm
- IR – B 1400 nm to 3000 nm
- IR – C 3000nm to 1 mm

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Biological effects

- As same as those produced by exposure to incoherent radiation of the same wavelength
- No significance biological due temporal and spatial coherence
- The monochromaticity has some significance in that a very small image can be formed on the retina
- High irradiance and the low divergence have practical implications for the assessment of hazard

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Biological effects

- Laser radiation, unlike ionising radiation at the short-wavelength of the spectrum, does not penetrate deeply into the body and the eye and the skin are the only organ need to be considered
- Radiation in the visible and infrared A regions is especially hazardous to the eye, because of its penetration through the structure of the eye to the retina
- The effects on the other organ at risk, the skin, depend on the wavelength

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Biological effects

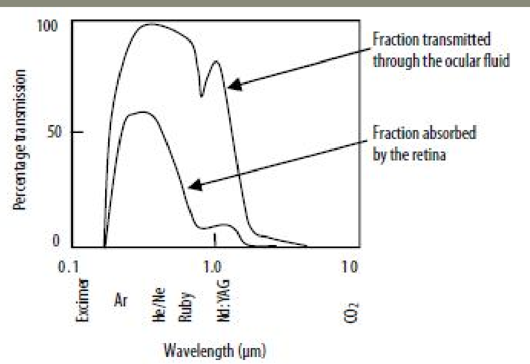

Figure 13.1 Spectral transmissivity of the ocular fluid and the absorptivity of the retina

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Biological effects

Table 13.1 Basic laser biological hazards

Laser type	Wavelength (μm)	Biological effects	Skin	Cornea	Lens	Retina
CO_2	10.6	Thermal	X	X		
H_2F_2	2.7	Thermal	X	X		
Er:YAG	1.54	Thermal	X	X		
Nd:YAG	1.33	Thermal	X	X	X	X
Nd:YAG	1.06	Thermal	X			X
GaAs diode	0.78–0.84	Thermal	–[a]		X	
He–Ne	0.633	Thermal	–[a]		X	
Ar	0.488–0.514	Thermal, photochemical	X			X
Excimer:						
XeF	0.351	Photochemical	X	X	X	
XeCl	0.308	Photochemical	X	X		
KrF	0.254	Photochemical	X	X		

[a] Insufficient power

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The main dangers from a laser

- Damage to the eye
- Damage to the skin
- Electrical hazards
- Hazards from fume

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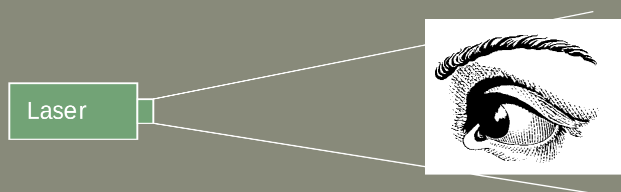
Direct Intrabeam Viewing



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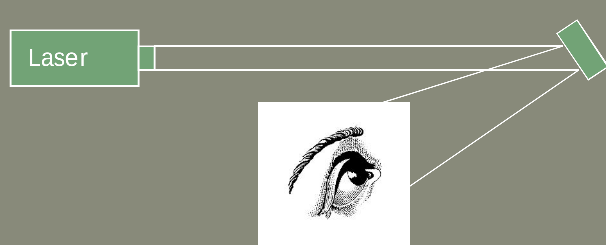
Specular Intrabeam Viewing



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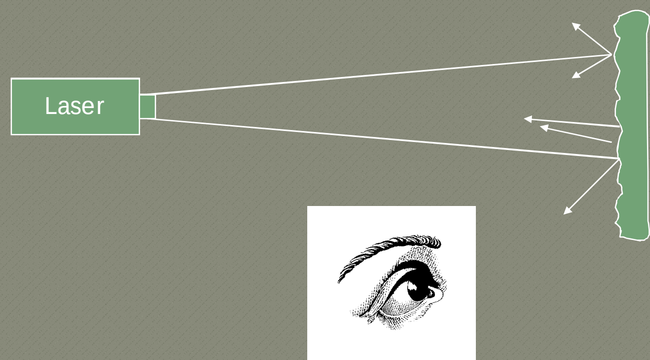
Diffuse Reflected Viewing



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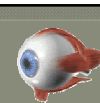
Laser Biological Hazards - Eyes



Near Ultraviolet Wavelengths (UVA) 315 - 400 nm
- Most of the radiation is absorbed in the lens of the eye.
- The effects are delayed and do not occur for many years (e.g.; cataracts).

Far Ultraviolet (UVB) 280 - 315 nm and (UVC) 100 - 280 nm
- Most of the radiation is absorbed in the cornea.
- Snow blindness/welder's flash) will result with high doses.

Visible (400 -760 nm) and Near Infrared (760 - 1400 nm)
- Most of the radiation is transmitted to the retina*.
- Overexposure may cause flash blindness or retinal burns and lesions.

Far Infrared (1400 nm - 1 mm)
- Most of the radiation is transmitted to the cornea.
- verexposure to these wavelengths will cause corneal burns.

Skin Hazards

- UV-A: Photosensitive reactions & tanning
- UV-B & IR: Sun burn (1000 x sensitive than UV-A to burns)
- UV-C: Skin burn (sunburns without tanning, not from sun)
- Skin cancer and accelerated skin aging

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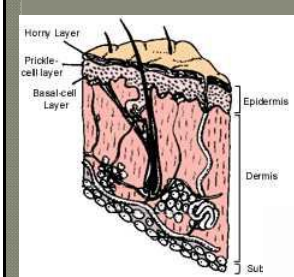
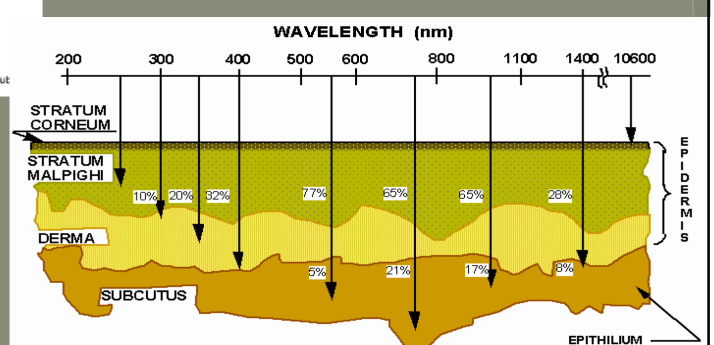
Laser Biological Hazards - Skin





Laser Biological Hazards - Skin

250 Watt Laser Moving at
1 Inch per Second

250 Watt Laser in Single Pulses

Laser Classification

- Laser classification is based on the damaging effects of the laser beam on the eyes and skin.
- Non-beam hazards are not considered in the classification.

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Class 1 Lasers (Exempt)

- Not capable of producing damaging radiation levels during normal operation.
- E.g. Laser printer, CD-Rom
- Does not apply to servicing.

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Class 2 & 3a Lasers (Low Power)

- **Class 2 lasers** emit visible light. Not hazardous if viewed less than 0.25 second. Maximum power is 1 mW for CW lasers. Eg. Barcode Scanner.
- **Class 3a lasers** probably not hazardous if viewed within 0.25 seconds. Hazardous if viewed with collecting optics. Maximum power is 5mW. Some require DANGER labels. E.g. Laser Pointer.

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Class 3b Lasers (Medium Power)

- Hazardous if viewed directly or by specular reflection. Diffuse reflection not usually hazardous. Upper limit is 0.5W for CW lasers.

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Class 4 lasers (high power)

- Lasers exceeding 0.5W
- Hazardous under all viewing conditions: direct, specular and diffuse.
- Potential fire hazard when in contact with combustible materials
- Produce skin hazards from ultraviolet radiation.
- Can produce laser generated air contaminants and hazardous plasma radiation.

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Safety class	Description
1	▪ Not dangerous under reasonable conditions of use either because the output of the laser is very low or because of installed safeguards ▪ Examples: 0.2-mW laser diode, fully enclosed 10W Nd:YAG laser ▪ Most commercial laser systems for material processing are sold as Class 1 products although they contain Class 4 lasers ▪ The benefit of a Class 1 laser system is that it can be installed anywhere and no eye protection is

Safety class	Description
2	The accessible laser radiation is limited to the visible spectral range (400–700 nm) and to 1 mW accessible power. Due to the blink reflex, it is not dangerous for the eye in the case of limited exposure (up to 0.25 s). Example: some (but not all) laser pointers
2M	Same as class 2, but with the additional restriction that no optical instruments may be used. The power may be higher than 1 mW, but the beam diameter in accessible areas is large enough to limit the intensity to levels which are safe for short-time exposure.

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Safety class	Description
3R	The accessible radiation may be dangerous for the eye, but can have at most 5 times the permissible optical power of class 2 (for visible radiation) or class 1 (for other wavelengths).
3B	The accessible radiation may be dangerous for the eye, and under special conditions also for the skin. Diffuse radiation (as e.g. scattered from the some diffuse target) should normally be harmless. Up to 500 mW is permitted in the visible spectral region. Example: 100-mW continuous-wave frequency-doubled Nd:YAG laser

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Safety class	description
4	The accessible radiation is very dangerous for the eye and for the skin. Even light from diffuse reflections may be hazardous for the eye. The radiation may cause fire or explosions. Examples: 10-W argon ion laser, 4-kW thin-disk laser in a non-encapsulated setup

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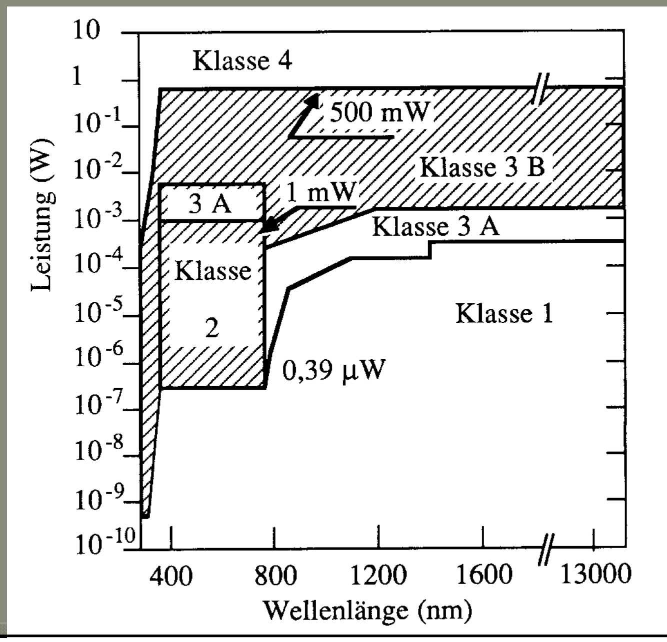
Laser Types and Classifications



Laser Types and Classifications

Table 1: Classification of CW lasers

Laser	Wavel.(nm)	Wavel. Range (nm)	Class 1(W)	Class 2(W)	Class 3(W)	Class 4(W)
cw Nd:YAG (quadrupled)	266	UV: 100 - 280	< 0.8×10^{-9} for 8 hrs	----	> Class 1 but < 0.5	> 0.5
He-Cd Argon Krypton	325 351.1, 363.8 350.7, 356.4	UV: 315 - 400	< 0.8×10^{-6}	----	> Class 1 but < 0.5	> 0.5
He-Cd Argon (vis.) He-Ne cw Nd:YAG dble He-Ne Krypton	441.6 488, 514.5 460, 4-700(numerous) 532 632.8 647.1, 530.9676.4	Visible: 400 - 700	< 0.4×10^{-6} < $0.4 \times C^B \times 10^{-6}$ (See ANSI Z136.1 for values of C^B)	> Class 1 but < 1×10^{-3}	> Class2 but < 0.5	> 0.5
cw Ga-Al-As cw Ga-As cw Nd:YAG He-Ne	850 (20° C) 905 (20° C) 1064 1080, 1152	Near IR: 700 -1400	< 80×10^{-6} < 0.1×10^{-3} < 0.28×10^{-3}	-------- ----	> Class 1 but < 0.5	> 0.5

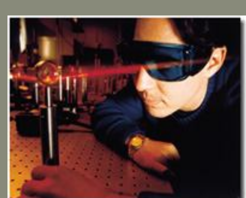
Laser Types and Classifications

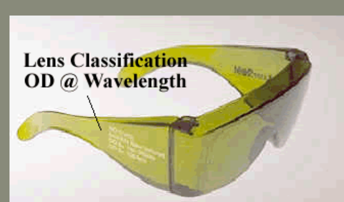
PULSED LASERS

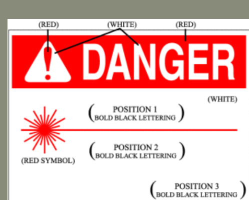
Laser	Wavel. (nm)	Pulse Duration(s)	Class 1 (J/ cm^2)	Class 3 (J/cm^2)	Class 4 (J/cm^2)
Nd:YAG Q sw. quad Ruby (Doubled)	266.1 347.1	10-30 x 10^{-9}	----	$\leq$ 10	> 10
Q sw Nd:YAG doubled Q switch Ruby Ruby long pulse Rhodamine 6G	532 694.3 694.3 450-650	~20 x 10^{-9} ,, ~1 x 10^{-3} ~1 x 10^{-6}	$\leq$ 0.2 x 10^{-6} $\leq$ 4.0 x 10^{-6} $\leq$ 0.2 x 10^{-6}	$\geq$ Class 1 but < 74 x 10^{-3} $\geq$ Class 1 but < 3.1 $\geq$ Class 1 but < 0.31	>75 x 10^{-3} >3.1 >0.31
Nd: YAG (Q sw) Erbium-glass (Q sw) Carbon Dioxide (Q sw)	1064 1540 10,600	~20 x 10^{-9} ~10-100 x 10^{-9} ~1-100 x 10^{-9}	$\leq$ 2 x 10^{-6} $\leq$ 8 x 10^{-3} $\leq$ 80 x 10^{-6}	$\geq$ Class 1 but < 0.16 $\geq$ Class 1 but < 10 $\geq$ Class 1 but < 10	> 0.16 >10 >10

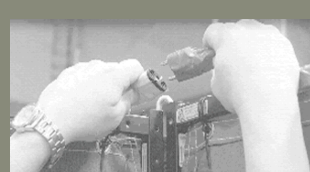
Based upon American National Standards Institute Standard Z-136.1

Protective Equipment









Protective Equipment

Protective Equipment

Simplified Method for Selecting Laser Eye Protection for Intrabeam Viewing for Wavelengths between 400 and 1400nm

Q-Switched Lasers (1 ns to 0.1 ms)		Non-Q-Switched Lasers (0.4 ms to 10 ms)		Continuous Lasers Momentary (0.25 s to 10 s)		Continuous Lasers Long-Term Staring Greater than 3 hours		Attenuation	
Maximum Output Energy (J)	Maximum Beam Radiant Exposure ($J \cdot cm^{-2}$)	Maximum Laser Output Energy (J)	Maximum Beam Radiant Exposure ($J \cdot cm^{-2}$)	Maximum Power Output (W)	Maximum Beam Irradiance ($W \cdot cm^{-2}$)	Maximum Power Output (W)	Maximum Beam Irradiance ($W \cdot cm^{-2}$)	Attenuation Factor	OD
10	20	100	200	NR	NR	NR	NR	100,000,000	8
1.0	2	10	20	NR	NR	NR	NR	10,000,000	7
10^{-1}	2×10^{-1}	1.0	2	NR	NR	1.0	2	1,000,000	6
10^{-2}	2×10^{-2}	10^{-1}	2×10^{-1}	NR	NR	10^{-1}	2×10^{-1}	100,000	5
10^{-3}	2×10^{-3}	10^{-2}	2×10^{-2}	10	20	10^{-2}	2×10^{-2}	10,000	4
10^{-4}	2×10^{-4}	10^{-3}	2×10^{-3}	1.0	2	10^{-3}	2×10^{-3}	1,000	3
10^{-5}	2×10^{-5}	10^{-4}	2×10^{-4}	10^{-1}	2×10^{-1}	10^{-4}	2×10^{-4}	100	2
10^{-6}	2×10^{-6}	10^{-5}	2×10^{-5}	10^{-2}	2×10^{-2}	10^{-5}	2×10^{-5}	10	1

NR = Not Recommended

Type of Accidents

- Eye exposure -73%
- Skin exposure -13.9%
- Fire -7.3%
- Electrical Shock -3.6 (5 deaths)

- Note: Contact DOHS to arrange a course in CPR.

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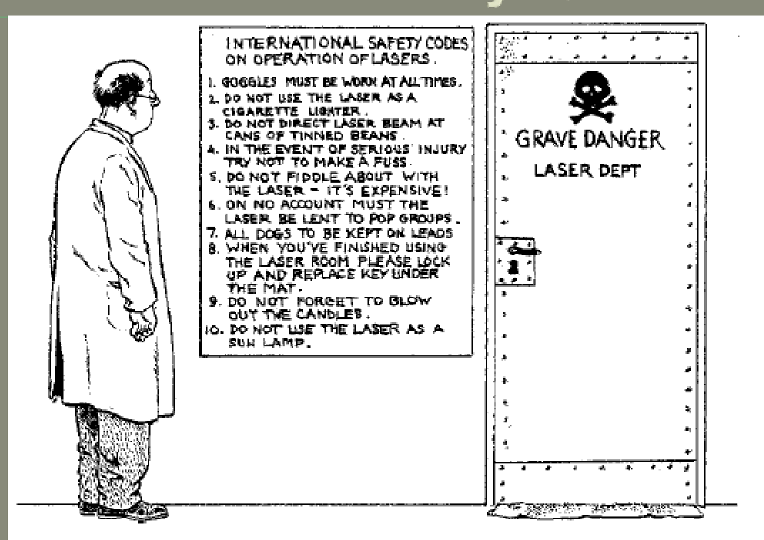
Any Question?



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