Introduction to Laser Material Processing

ME 677: Laser Material Processing

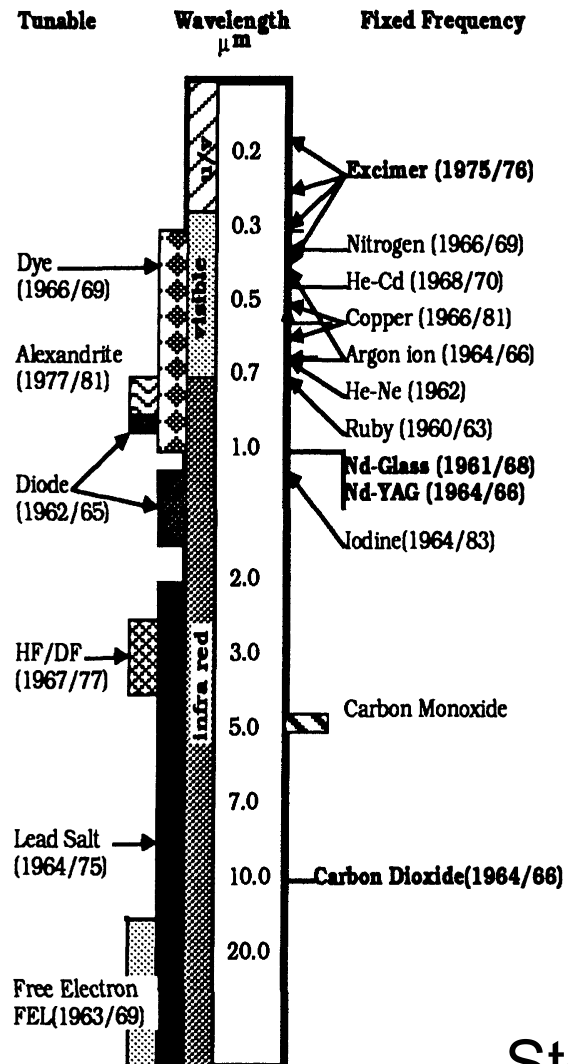
Instructor: Ramesh Singh

Outline

- Brief History
- Design of Laser cavity
- Stability
- Types of Lasers

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



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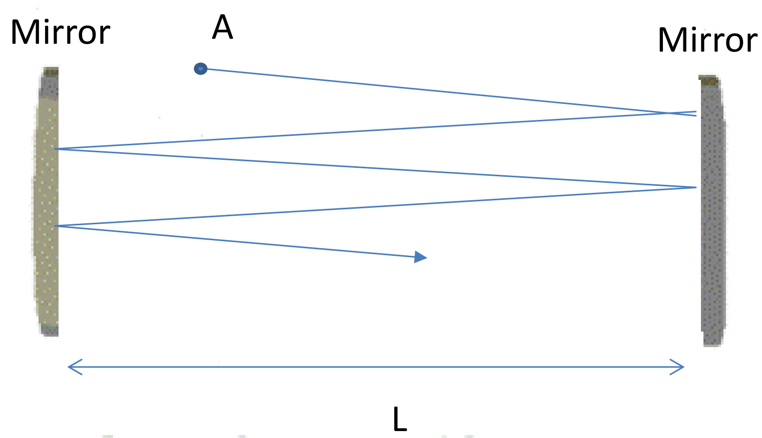
Optical Cavity Design: Frequency and length



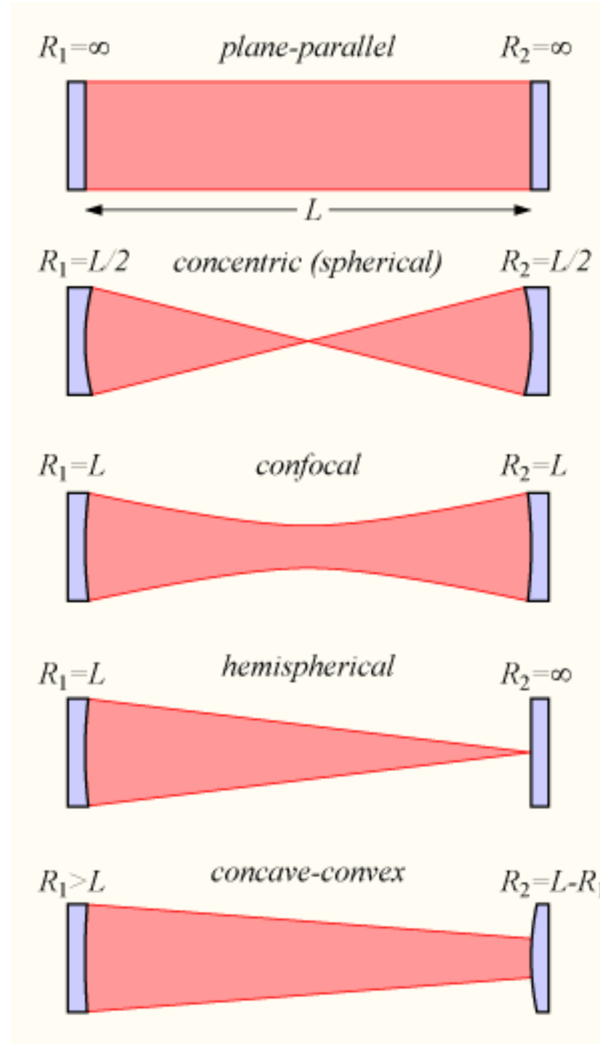
- Total electric field, E, at any point will be determined by the interference of the E fields from the various reflected waves
- Assuming the phase of the E field is same after traversing a distance 2L

$$E(x,t) = E_0 \cos(kx - \omega t)$$
$$E(x + 2L, t) = E(x,t)$$
$$k2L = m2\pi$$
$$2L = m\lambda$$
$$\upsilon_m = \frac{c/n}{\lambda} = m\frac{c}{2nL}$$

The output frequency is function of Refractive index and length

Optical Cavity Design

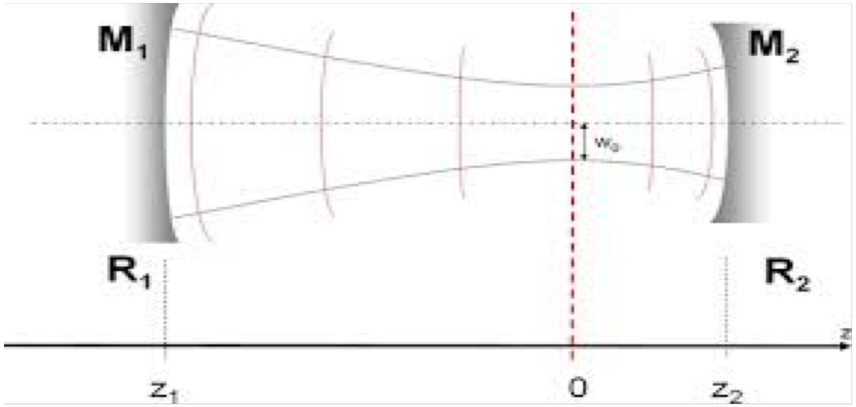
- Basic designs components
  - Totally reflecting mirror
  - Partially reflecting mirror
  - Mirror materials
    - ZnSe, GaAs and CdTe for $C0_2$ lasers
    - BK7 fused Silica
  - Key parameters
    - R1, R2, L
  - Multiple configurations



Stability of Laser Cavity

- Laser cavity could have two configurations:
  - Stable
  - Unstable
    - If the cavity is unstable, the beam size will grow without limit, eventually growing larger than the size of the cavity mirrors and being lost

Stability of Optical Cavity



A general spherical resonator formed by two mirrors M_1 and M_2 separated by a distance $L= z_2-z_1$ having radii of curvatures, R_1 and R_2, respectively

$$R(z) = z\left(1 + \frac{\pi^2 w_0^4}{\lambda^2 z^2}\right) = z + \frac{K}{z} \qquad K = \frac{\pi^2 w_0^4}{\lambda^2}$$

If the beam waist is located at z=0, the beam size of the Gaussian beam at plane z, $w(z)$, is given by:

$$w(z) = w_0\left(1 + \frac{\lambda^2 z^2}{\pi^2 w_0^4}\right)^{0.5}$$

Stability Analysis

$$z_1 + \frac{K}{z_1} = -R_1;\ z_2 + \frac{K}{z_2} = R_2$$

$$z_2 - z_1 = L$$

$$z_2 = \frac{L(L - R_1)}{(2L - R_1 - R_2)}$$

$$g_1 = 1 - \frac{L}{R_1};\ g_2 = 1 - \frac{L}{R_2}$$

$$z_2 = \frac{L(1-g_2)g_1}{(g_1+g_2-2g_1g_2)};\ z_1 = -\frac{L(1-g_1)g_2}{(g_1+g_2-2g_1g_2)}$$

$$K = \frac{L^2(1 - g_1g_2)g_1g_2}{(g_1 + g_2 - 2g_1g_2)^2}$$

Stability Analysis

$$w^2(z_1) = \frac{\lambda L}{\pi}\left(\frac{g_2}{g_1(1-g_1 g_2)}\right)^{\frac{1}{2}}$$

$$w^2(z_2) = \frac{\lambda L}{\pi}\left(\frac{g_1}{g_2(1-g_1 g_2)}\right)^{\frac{1}{2}}$$

- Above equation gives
- g1.g2=1 or g1.g2=0 are unfeasible and analysis breaks down.

Stability analysis for Optical Cavity

- Ray transfer matrix analysis

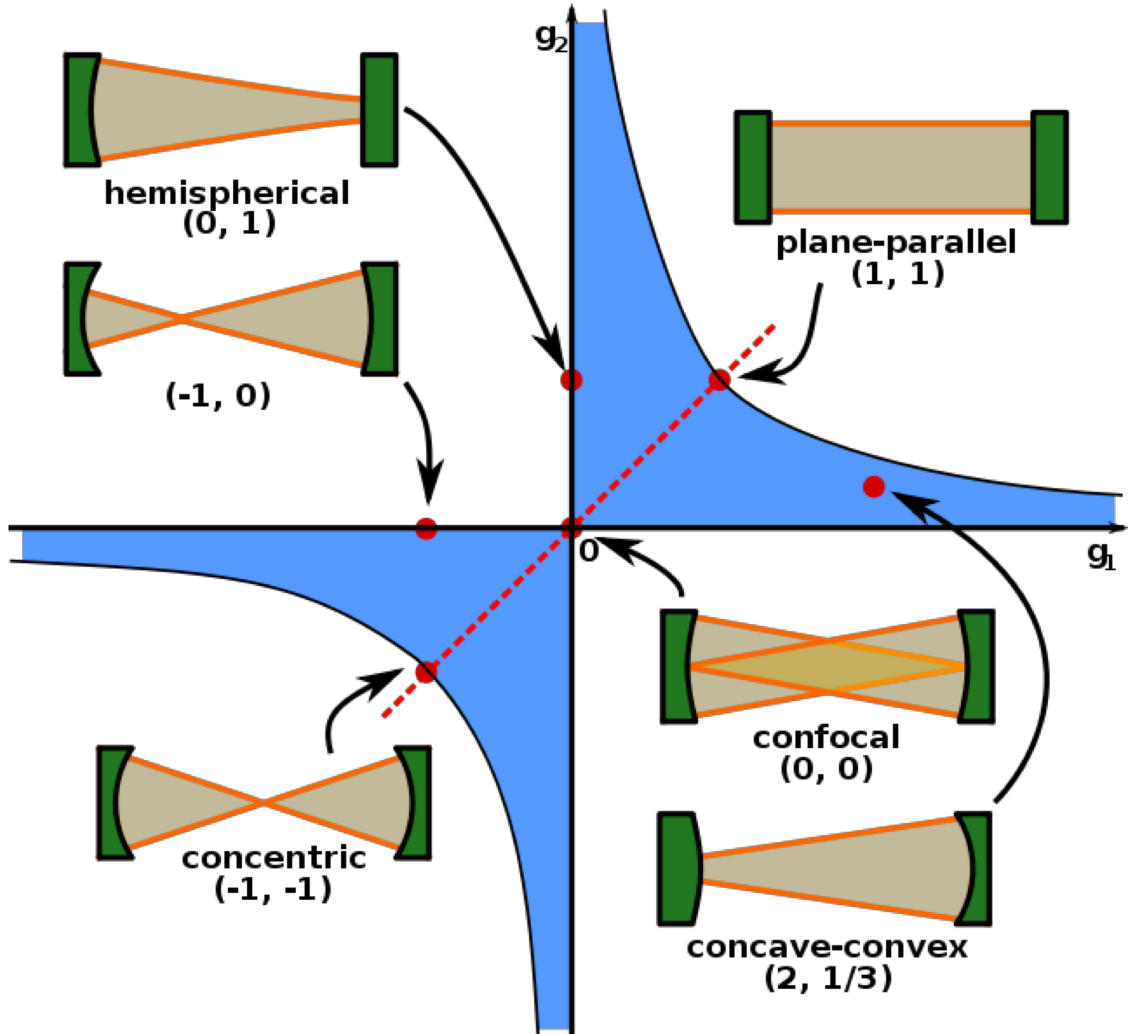
$$0 \le \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \le 1$$

$$g_1 = \left(1-\frac{L}{R_1}\right)$$

$$g_2 = \left(1-\frac{L}{R_2}\right)$$

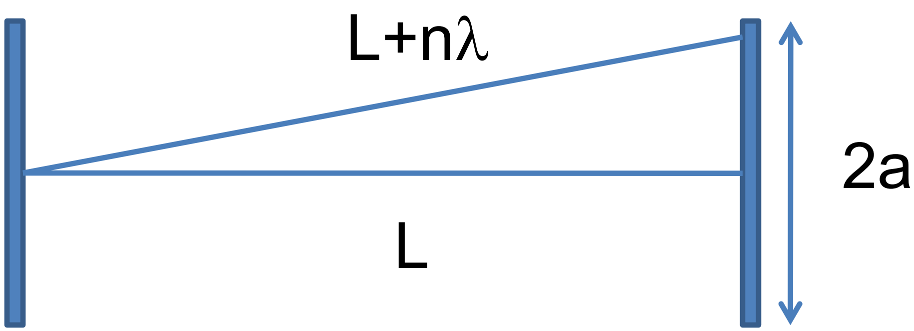
Plot of stability

- $0 \leq g1.g2 \leq 1$



Cavity Length

- The cavity length/width of aperture determines number of off-axis modes between the mirrors
  - L = cavity length
  - a = radius of aperture
  - λ = wavelength of laser radiation
  - n = number of fringes or off axis modes



Fresnel Number

- Using Pythagoras Theorem and ignoring higher order terms,

$$a^2 + L^2 = (L + n\lambda)^2$$

$$a^2 = 2Ln\lambda$$

$$n = \frac{a^2}{2L\lambda}$$

- n = Fresnel Number/2
- Total number of fringes observed if the back mirror is uniformly illuminated

Fresnel No. (Contd.)

- Low Fresnel number gives low-order mode
- Off axis oscillations are lost in diffraction
- A high Fresnel number cavity can be controlled by using mirror design
  - Flatter of Curved?

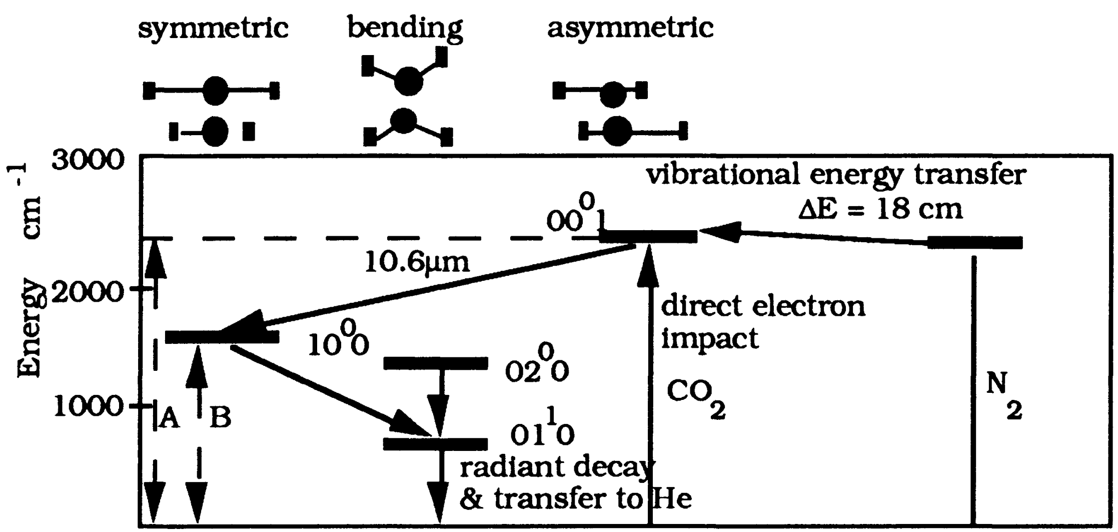
- Off axis modes define Transverse Electromagnetic Mode

Types of Lasers

- 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

CO_2 Lasers

- The traveling photon formed due to energy loss or collision:
  - It can take molecule 10^00 to 00^01
  - Get diffracted
  - Strike the excited molecule at higher energy
- The molecule at higher energy will emit photon of identical wavelength in same phase and direction



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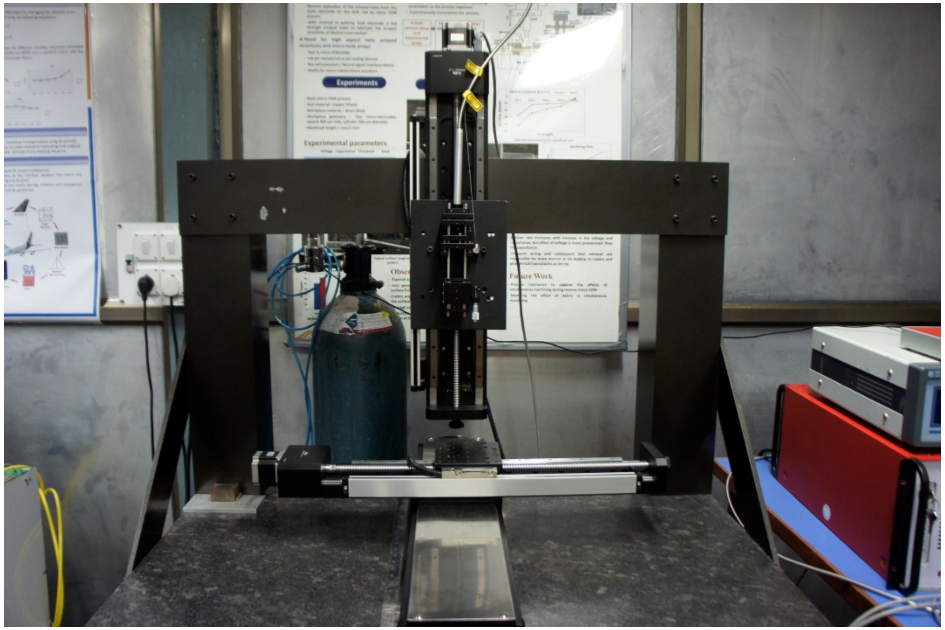
KrF Excimer Laser at IIT Bombay

- No oscillator
- Very High Powers (0.2 J/pulse on 20 ns pulse width)
- Expensive

Fiber Laser at IIT Bombay

- 100 W CW
- Frequency 100 KHz
- Pulse width of the order of μs

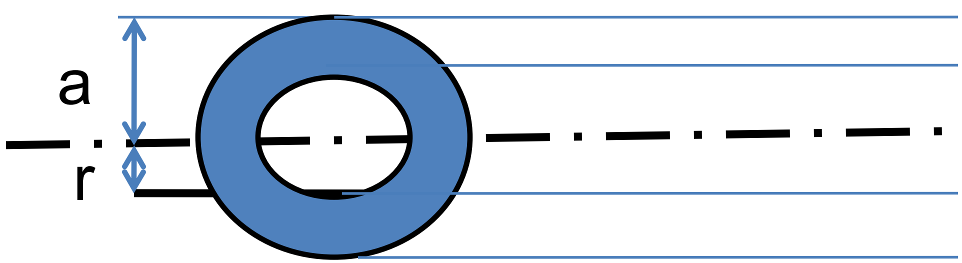


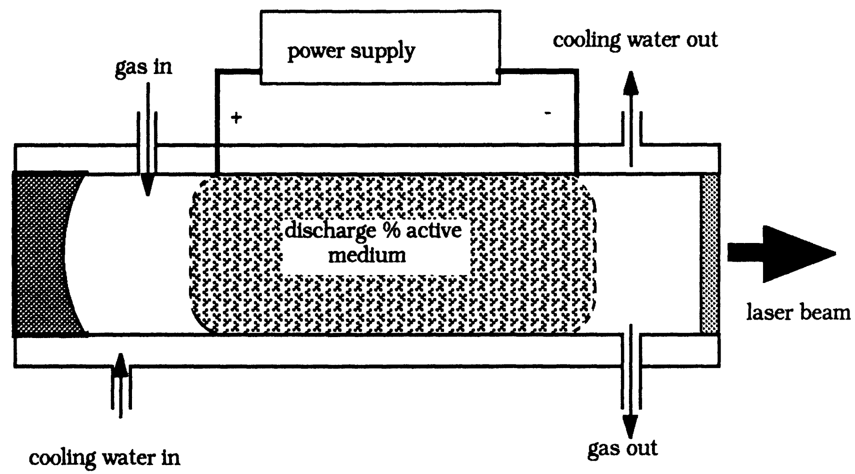
3 kW Fiber Laser @ IITB

3 kW Fiber laser

Industrial Lasers-Slow Flow

- Slow Flow Lasers
  - Cooling through walls of the cavity
- Analysis of cooling in slow flow lasers
  - Heat generated/length = $Q\pi r^2$
  - Heat removed/length = $-2\pi rk(dT/dr)$
  - Q= rate of volumetric heat flow





Analysis for Slow Flow Lasers

$$\int_{T}^{Tc} dT = \int_{r}^{a} -\frac{Qr}{2k} dr$$

$$Max Temp @ r = 0, T\max = Taxis$$

$$Taxis = \frac{Qa^2}{4k} + Tc$$

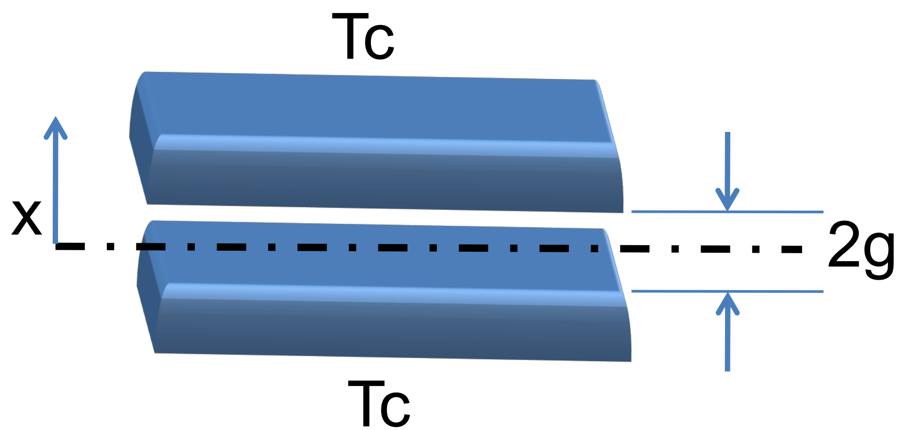
$$Volumetric\_Heat,$$

$$\eta Q = \frac{P}{\pi a^2 L}$$

$$P = 4\pi\eta k L (T\max - Tc)$$

Slow Flow-Waveguide Cooling

- A variation of conduction route
  - Thin slit between electrodes is the laser cavity
  - Laser is wave guided within the narrow passage
- Analysis of cooling in slow flow lasers
  - Heat generated in cross-section A, and thickness, x = QAx
  - Heat removed by conduction = *-kA(dT/dx)*



Waveguide Analysis

$$\int_{T}^{Tc} dT = \int_{x}^{g} -\frac{Qx}{k} dx$$

$$MaxTemp @ x = 0, T\max = Taxis$$

$$Taxis = \frac{Qg^2}{2k} + Tc$$

$$Volumetric\_Heat,$$

$$\eta Q = \frac{P}{A2g}$$

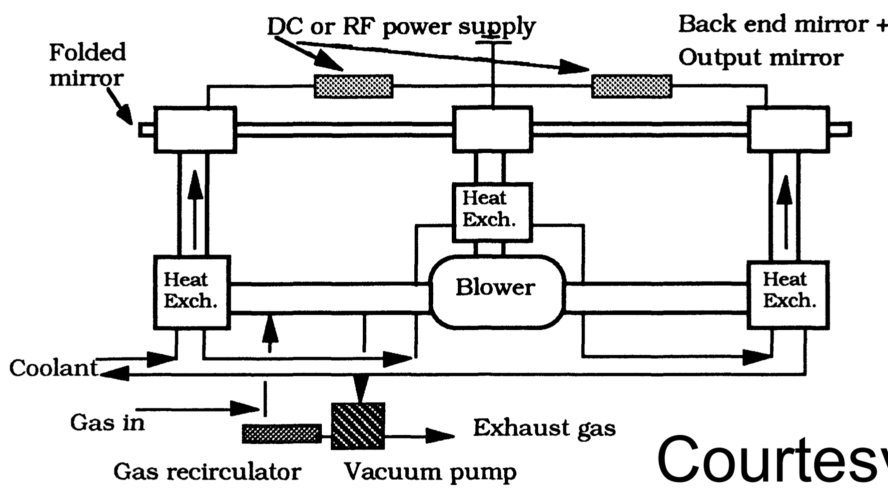
$$P = 4\frac{A}{g}\eta k(T\max - Tc)$$

Slow-Flow Lasers

- Cooling efficiency governs the output power
- 50W/m -80 W/m output power
- Good mode for rod systems
- Elliptical profile and arrayed beams for wave guide

Fast Axial Flow Lasers

- Fast axial flow lasers
  - Gas flow rates 300-500 m/s in discharge zone
  - Cavity length is of low Fresnel number
  - Good for high power compact lasers
  - Cooling is done by the flowing gas during its time of interaction in discharge zone



Courtesy: Steen 3rdEdition

Analysis – Fast Axial Flow

$$\delta \mathrm{Q} = -Q.dt$$

$$where\ \mathrm{Q}\ =\ \text{Volumetric heat (J/m}^3\text{)}$$

$$Q = \text{rate of volumetric heat generation } (W\ /\ m^3)$$

$$\int_{T}^{T_c} \rho C dT = -\int_{x}^{L} \frac{Q.dx}{V}$$

$$\eta Q = \frac{P}{AL}$$

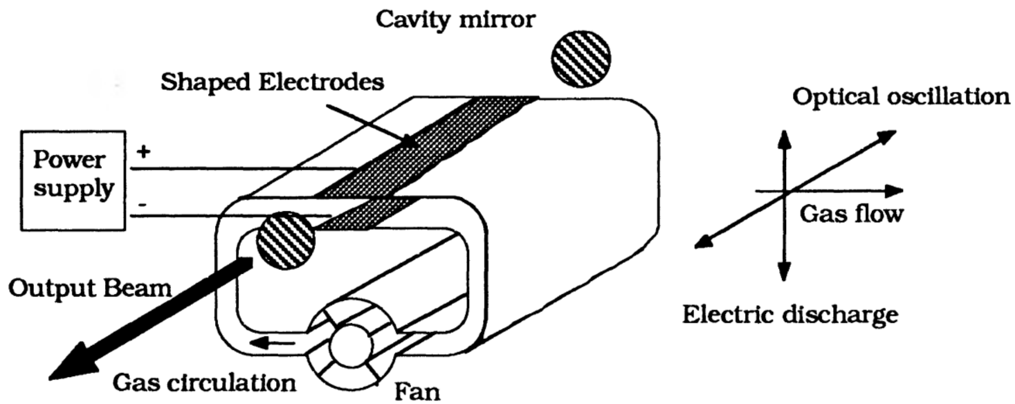
$$P = \eta \rho A V C (T\max - Tc)$$

Fast Axial Flow Lasers

- Power is proportional to area and velocity
- Mode number $a^2/L\lambda \sim A/L\lambda$ is typically very high and difficult to focus finely
- Very high power generation
  - 650 W/m

Transverse Flow Lasers

- For very high powers lasers are convectively cooled in transverse direction



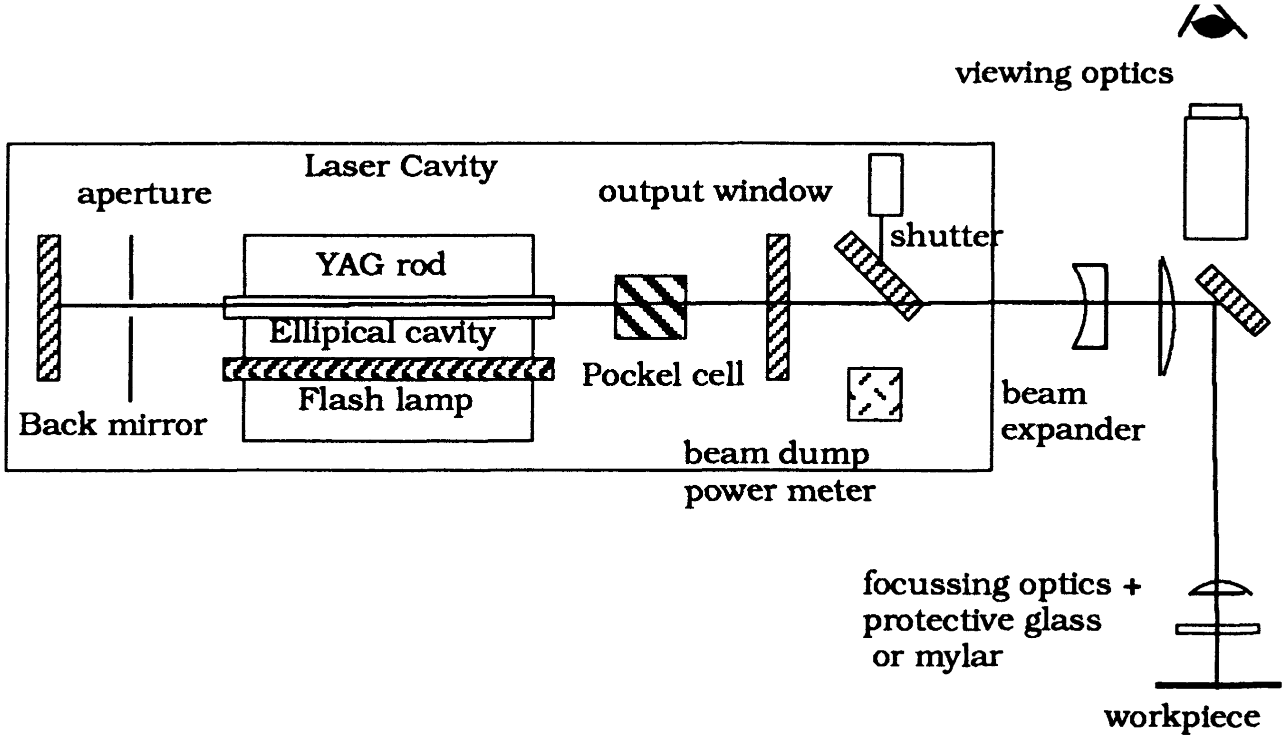
- Asymmetric beam power due to heating of the gas while traversing the lasing space
- Asymmetric beam power is obtained
- UTRC 25 KW laser, MLI laser

UTRC Laser

Solid State Lasers

- Solid state lasers have three key design features
  - Pumping power for lasing
  - Cooling
  - Avoiding distortion or breakage due to thermal load
- Nd-YAG
  - Pumped by flash lamp or diode
  - Nd^{3+} ions in YAG rod
  - Q switching for pulse rates (0-50 kHz)
    - Spoils lasing oscillation in controlled way
    - Mechanical chopper, bleachable dye, optoelectric shutter, acousto-optic switch

Nd-YAG Construction



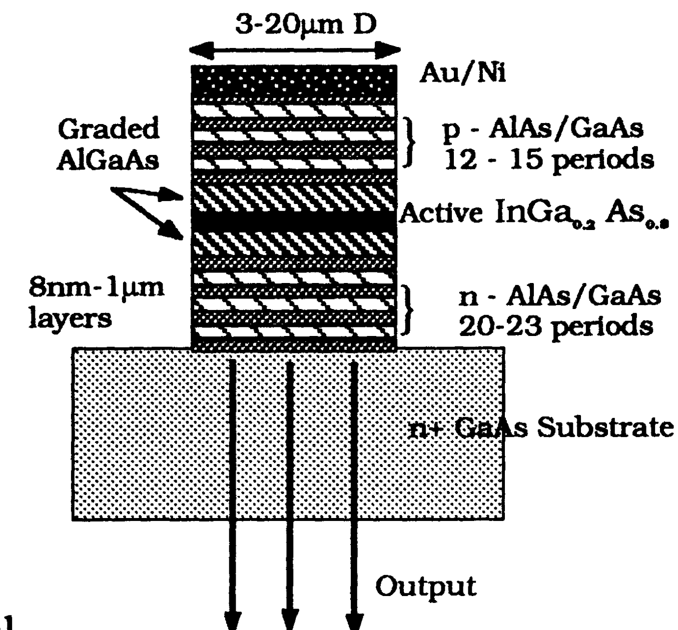
- Nd-YAG laser can be passed through barium borate (BBO) or lithium niobate (LBO) crystals can yield 530 nm
- This process is called frequency doubling

Diode Pumped Solid State Lasers

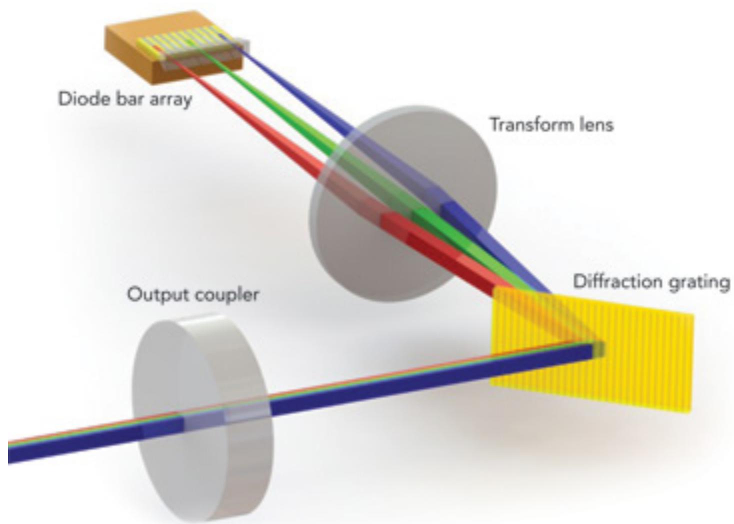
- Tiny fraction of the power is absorbed by Nd^{3+}
- Waste heat causes distortion
- Diode lasers have high wall plug efficiency and good coupling with Nd^{3+}

Diode Lasers

- Similar to LED
- Difference in Fermi energy in conduction and valence band at p-n junction
- Photons can be emitted
- Stacked configuration



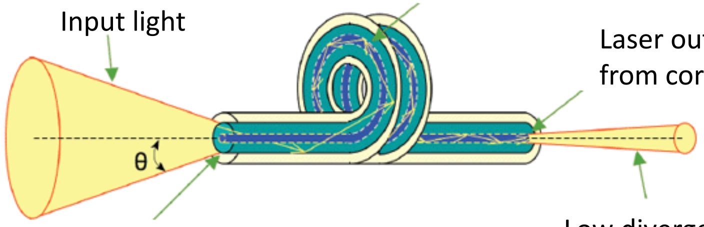
High Power Diode Lasers



Diode Pumped Fiber Lasers

- A laser in which the active gain medium is an optical fiber doped with rare-earth elements
  - Erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium
- Doped fiber amplifiers provide light amplification without lasing
- Pumped by diode lasers

Fiber Laser


Rare earth doped core
Input light
Laser output
from core
θ
Double clad
Low divergence
single mode beam

Advantages

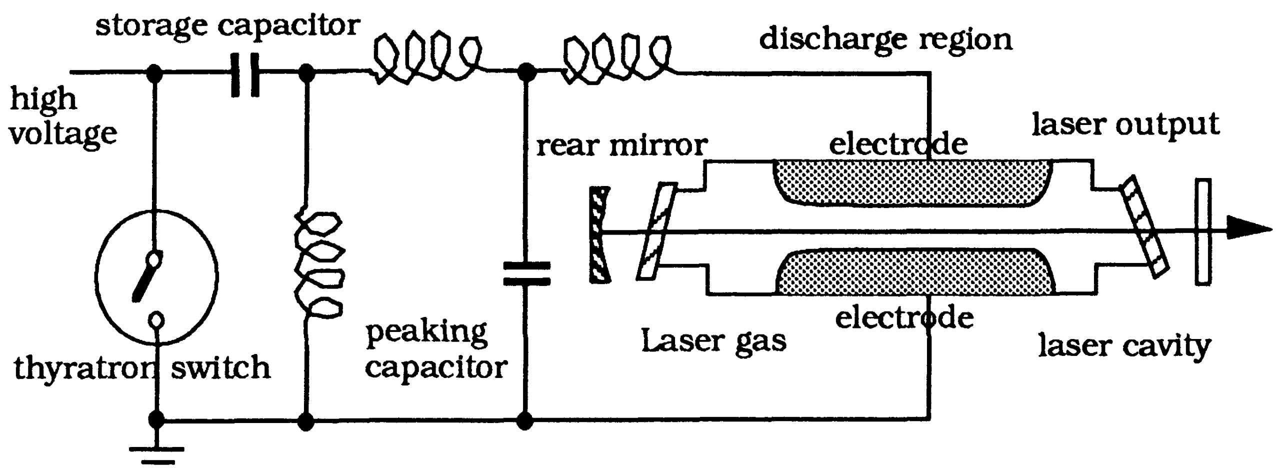
- High beam quality
- High wall plug efficiency
- Portability
- Long life

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.								

Functioning of Excimer Laser

- Excitation by 35-50 kv pulse
- Current density up to 1 kA/cm²
- Optics
  - Fused silica,
- Gas 4-5 MPa



Excimer Laser Reactions

Pumping (Mirowave or gas discharge is used),
e + Kr →Kr+ + e + e
Positive inert gas ion formation,

e + Kr → Kr* + e
Inert gas in metastable condition,

e + F2 → F-+ F+
Negative halogen ion formation,

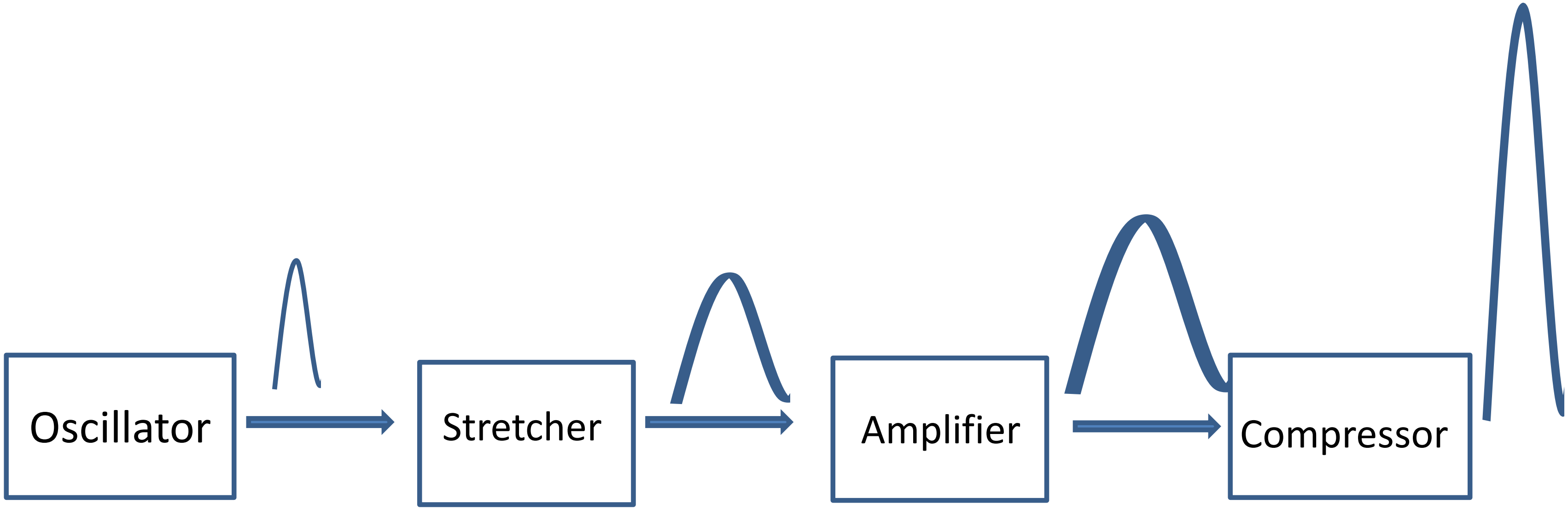
Kr* + F-+ M → KrF* + M
KrF production,
Kr* + F2 → KrF* + F

Stimulated emission,
KrF* + hv → Kr + F + 2hv (248 nm) -laser emission

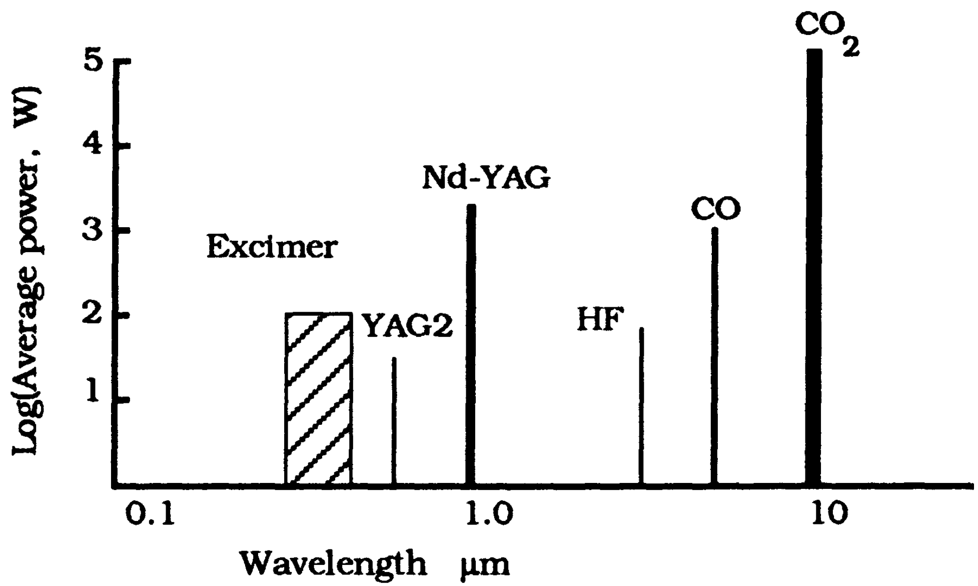
Ultra Short Pulsed Lasers

- Ultrashort Pulse Lasers: Most of the lasers operate in a CW mode or pulsed mode of the order of 100 picoseconds by either q-switching or mode locking.
- Ultrashort pulsed are lasers which have femtosecond duration pulses. This ultrashort pulse duration enables very high peak powers (~10^{15} W/cm^2).
- Many methods have been developed for creating ultrashort pulse laser beams. However, one of the basic methods is chirped pulse amplification.
  - It is known that the spectrum of the laser beam is inversely proportional to the pulse duration. Hence, a laser gain medium with broad continuous spectrum is essential for ultrashort pulse.
  - The active media that can support femtosecond lasers are Ti-Sapphire (6 fs), Nd:Glass (100 fs), Yb:Glass, Yb:YAG, Cr:YAG, and dye.
  - The generation starts from mode locking which results in a frequency of 100 MHz.

Chirped Pulse Amplification



Comparison Between Lasers -Power

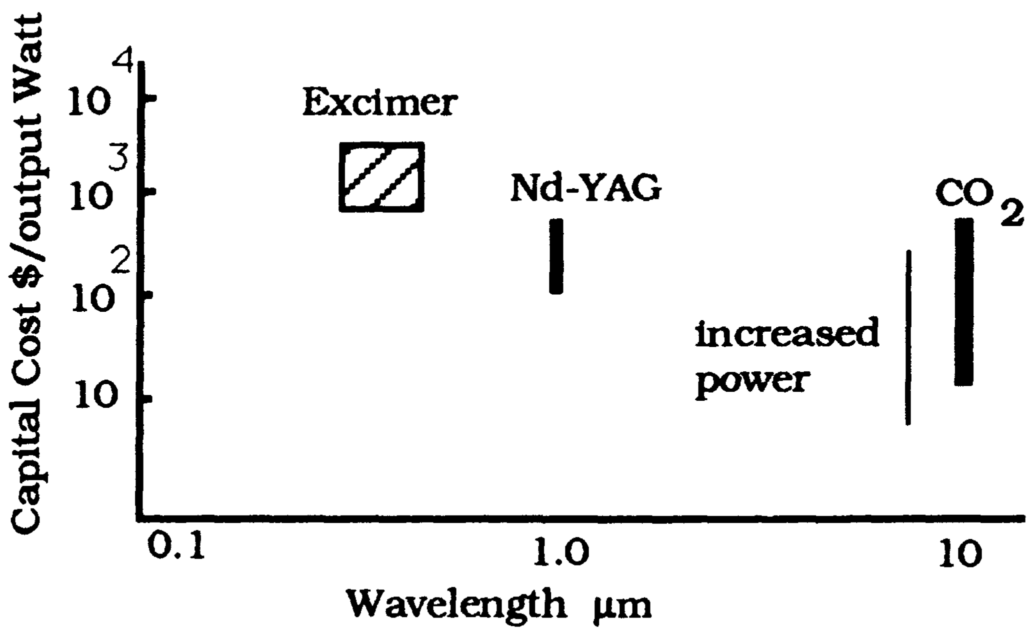


Efficiency-1

Table 1.2	Efficiency of main types of industrial lasers	
Type	Wavelength μm	Wall Plug Efficiency %
Carbon Dioxide	10.6	12
Carbon Monoxide	5.4	8
Nd-YAG	1.06	0.4
Nd-Glass	1.06	0.1
Excimer (KrF)	0.249	2

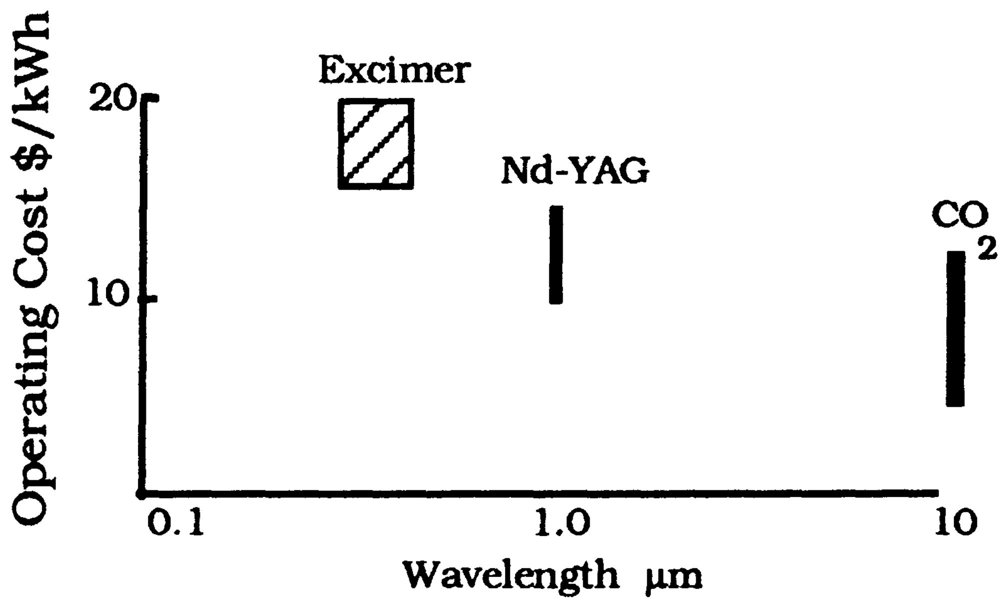
Capital Cost

- 1987 data



Operating Cost

- 1987 data

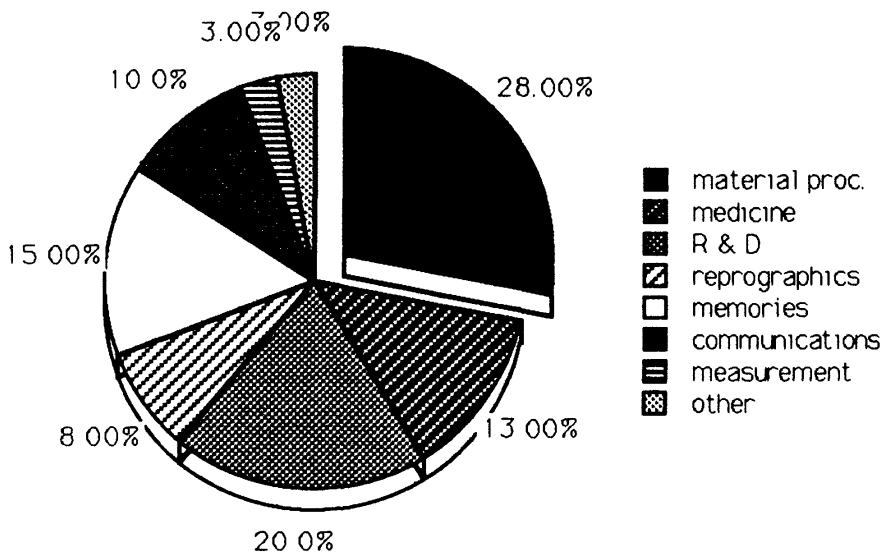


Comparison with Fiber

Properties of various lasers (courtesy IPG Photonics)

Properties	**Fiber Laser**	**Nd:YAG**	**CO_2**	**Disc**
Wall Plug Efficiency	30%	~ 5%	~10%	15%
Output Powers	to 50kW	to 6kW	to 20Kw	to 4kW
BPP (4/5 kW)	< 2.5	25	6	8
Life	100,000	10,000	N.A.	10,000
Cooling	Air/water	water	water	water
Floor Space (4/5 kW)	< 1 sq. m	6 sq. m	3 sq. m	4 sq. m
Operating Cost	$21.31	$38.33	$24.27	$35.43
Maintenance	Not Required	Often	Required	Often

Market Share



Laser-Summary

- Types of Lasers
- Optical cavity Design
- Cooling
- Comparative study