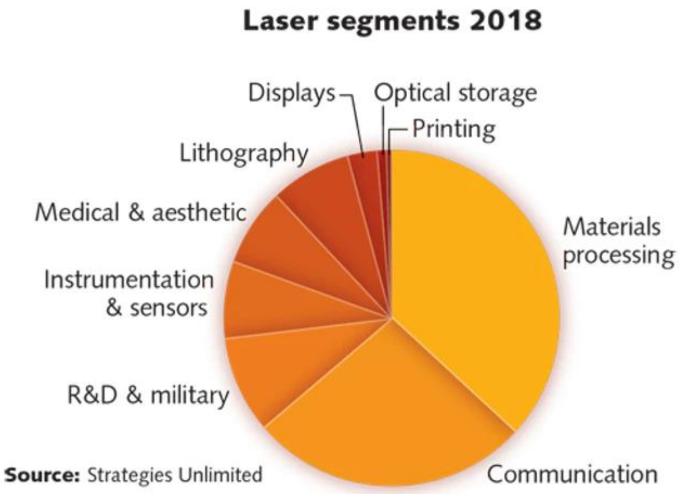
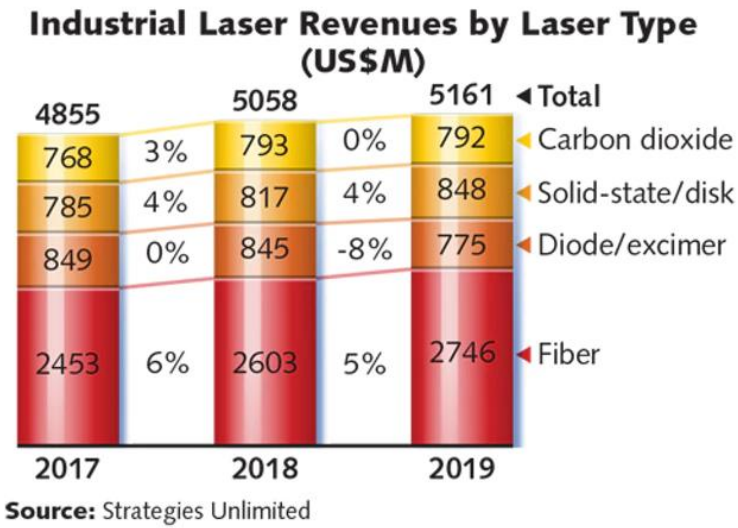
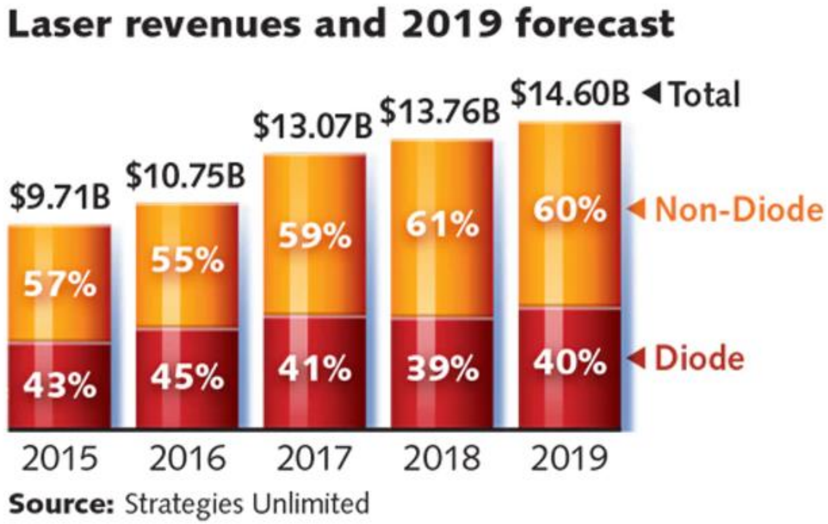
Examples of Specific Laser Systems

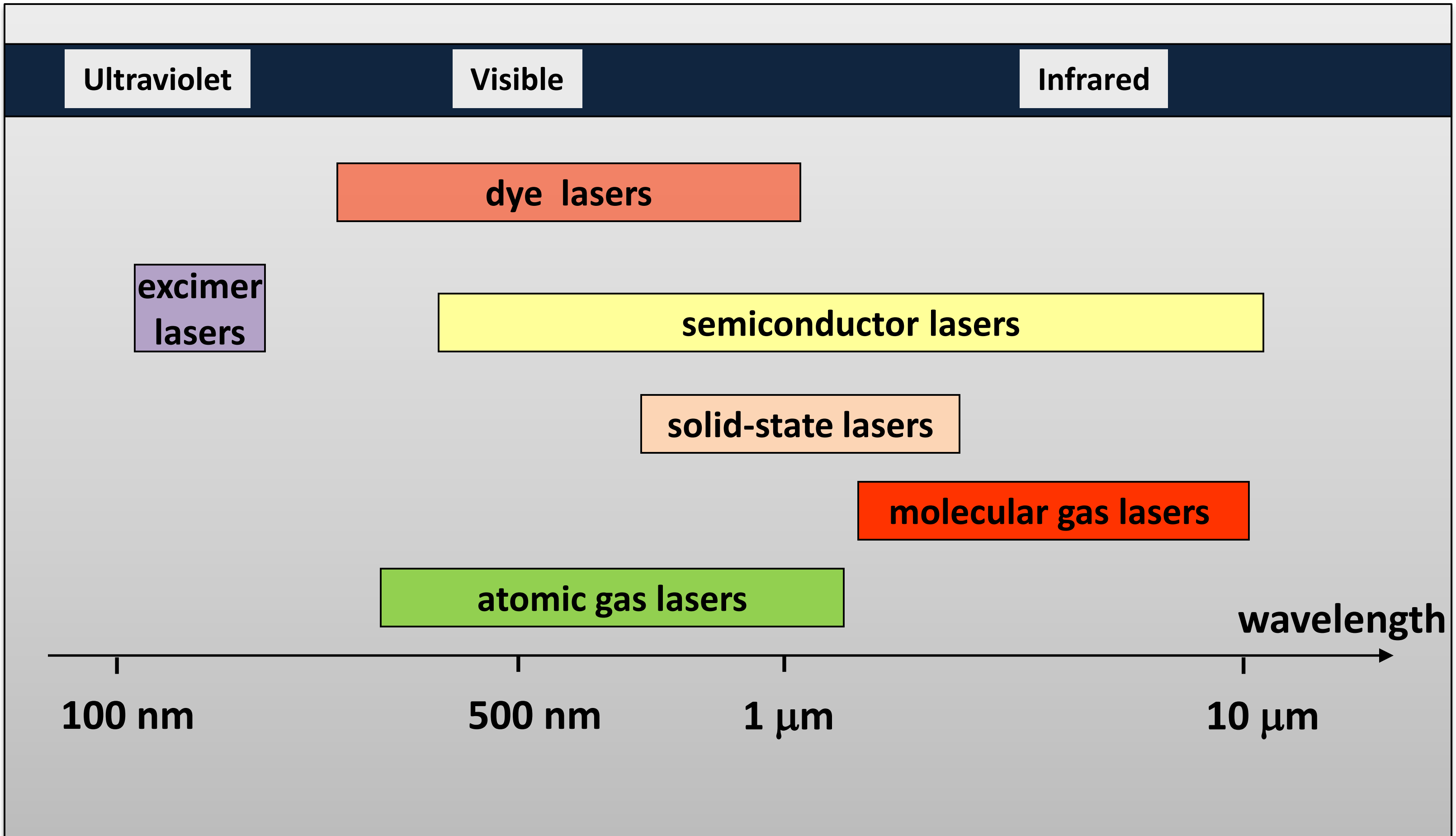
- Gas Lasers
  - CO_2 (9-10 μm), High Power
  - He:Ne (632 nm) , Ar (ion) Laser (520 nm)
  - Excimer (UV) Lithography
- Solid-State Lasers
  - Nd:YAG , Ti:Sapphire (Ultrafast Revolution)
- Fiber Lasers (Rare-Earth Doped Fiber Lasers)
  - Yb^{3+} (5+ kW), Tm^{3+} , Ho^{3+} (2 μm), Er^{3+} (1.5 μm)
- Dye Lasers
- Chemical Lasers
  - COIL (7+kW), MIRACL (>1 MW !!)
- Semiconductor Lasers

Laser Market and Applications

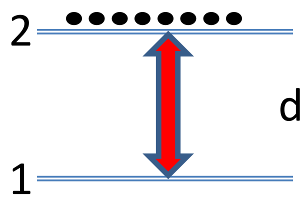







Ultraviolet
Visible
Infrared
dye lasers
excimer lasers
semiconductor lasers
solid-state lasers
molecular gas lasers
atomic gas lasers
wavelength
100 nm
500 nm
1 μm
10 μm

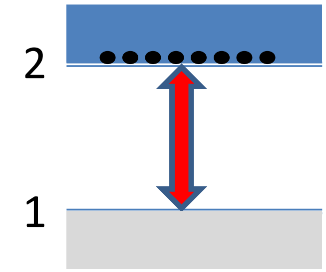
Optical Transitions



discrete levels

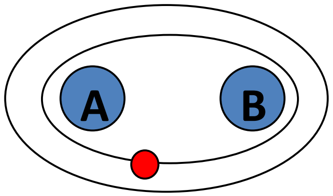
OR

energy bands



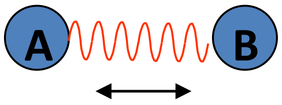
emission

electronic transitions



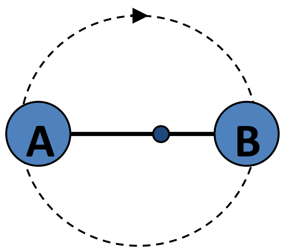
VIS, UV

vibrational transitions

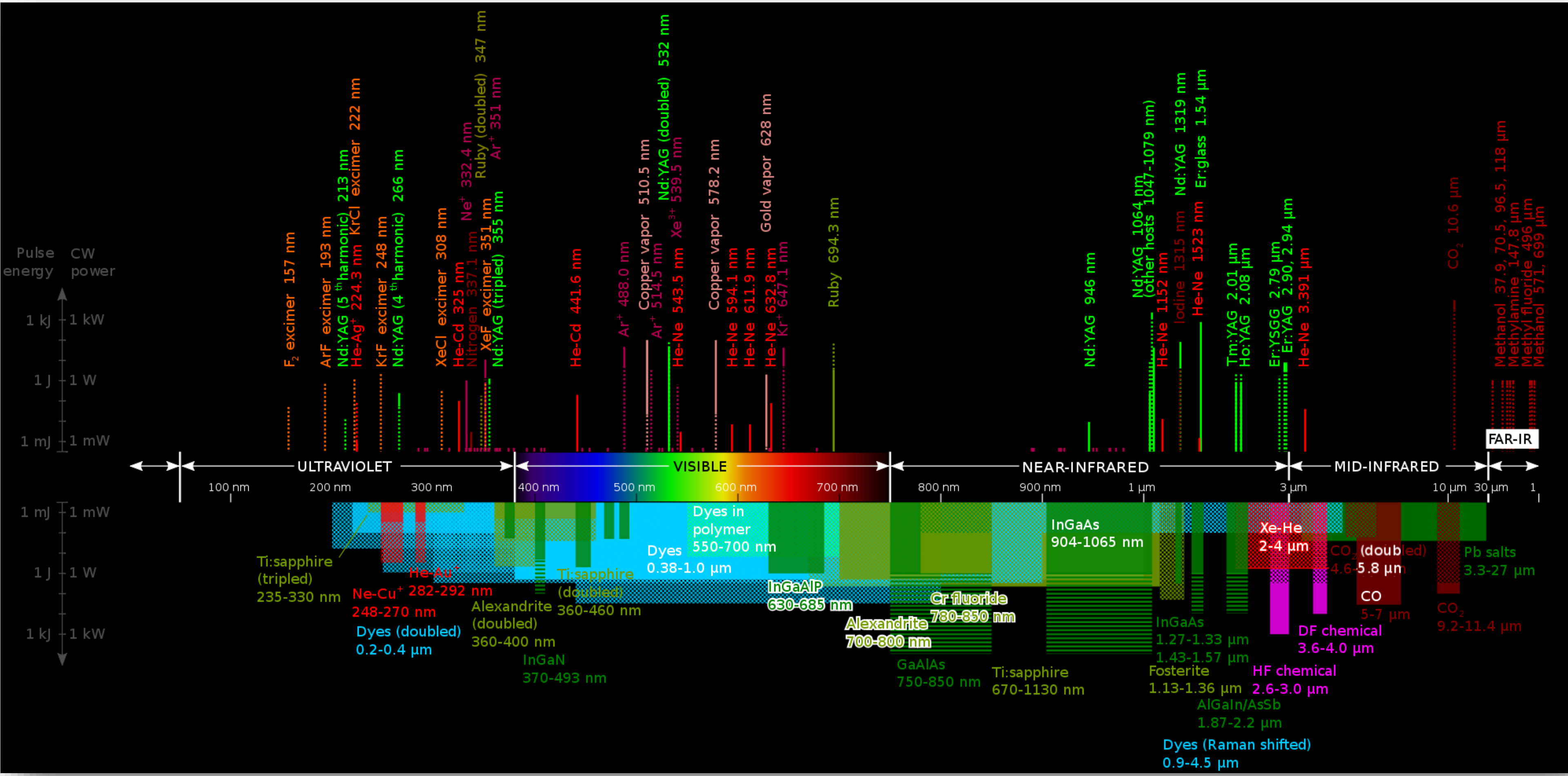


NIR, IR

rotational transitions



FIR



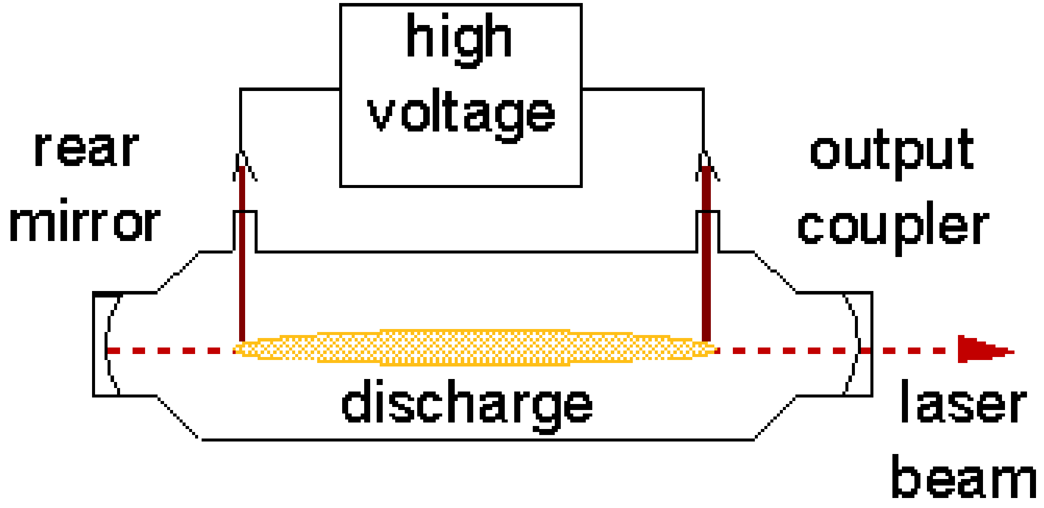
Pulse energy
CW power
1 kJ
1 kW
1 J
1 W
1 mJ
1 mW
ULTRAVIOLET
VISIBLE
NEAR-INFRARED
MID-INFRARED
FAR-IR
100 nm
200 nm
300 nm
400 nm
500 nm
600 nm
700 nm
800 nm
900 nm
1 μm
3 μm
10 μm
30 μm
F2 excimer 157 nm
ArF excimer 193 nm
Nd:YAG (5th harmonic) 213 nm
He-Ag+ 224.3 nm
KrCl excimer 222 nm
KrF excimer 248 nm
Nd:YAG (4th harmonic) 266 nm
XeCl excimer 308 nm
He-Cd 325 nm
Nitrogen 337.1 nm
Ne+ 332.4 nm
XeF excimer 351 nm
Nd:YAG (tripled) 355 nm
Ruby (doubled) 347 nm
Ar+ 351 nm
He-Cd 441.6 nm
Ar+ 488.0 nm
Ar+ 514.5 nm
Copper vapor 510.5 nm
Nd:YAG (doubled) 532 nm
Xe3+ 539.5 nm
He-Ne 543.5 nm
Copper vapor 578.2 nm
He-Ne 594.1 nm
He-Ne 611.9 nm
Gold vapor 628 nm
He-Ne 632.8 nm
Kr+ 647.1 nm
Ruby 694.3 nm
Nd:YAG 946 nm
Nd:YAG 1064 nm (other hosts 1047-1079 nm)
He-Ne 1152 nm
Iodine 1315 nm
Nd:YAG 1319 nm
He-Ne 1523 nm
Er:glass 1.54 μm
Tm:YAG 2.01 μm
Ho:YAG 2.08 μm
Er:YSGG 2.79 μm
Er:YAG 2.90, 2.94 μm
He-Ne 3.391 μm
CO2 10.6 μm
Methanol 37.9, 70.5, 96.5, 118 μm
Methylamine 147.8 μm
Methyl fluoride 496 μm
Methanol 571, 699 μm
Ti:sapphire (tripled) 235-330 nm
Ne-Cu+ 248-270 nm
He-Au+ 282-292 nm
Dyes (doubled) 0.2-0.4 μm
Alexandrite (doubled) 360-400 nm
InGaN 370-493 nm
Ti:sapphire (doubled) 360-460 nm
Dyes 0.38-1.0 μm
Dyes in polymer 550-700 nm
InGaAlP 630-685 nm
Alexandrite 700-800 nm
Cr fluoride 780-850 nm
GaAlAs 750-850 nm
Ti:sapphire 670-1130 nm
InGaAs 904-1065 nm
InGaAs 1.27-1.33 μm 1.43-1.57 μm
Fosterite 1.13-1.36 μm
AlGaIn/AsSb 1.87-2.2 μm
Dyes (Raman shifted) 0.9-4.5 μm
Xe-He 2-4 μm
HF chemical 2.6-3.0 μm
DF chemical 3.6-4.0 μm
CO2 (doubled) 4.6-5.8 μm
CO 5-7 μm
CO2 9.2-11.4 μm
Pb salts 3.3-27 μm

Typical laser efficiencies η :

$$\eta = \frac{\text{output power}}{\text{electrical input power}}$$

Argon - ion	< 0.1%
CO_2 laser	< 20%
Excimer	< 20%
GaAlAs (diode laser)	< 40%
HeNe	< 0.1%
Nd:YAG	< 10%

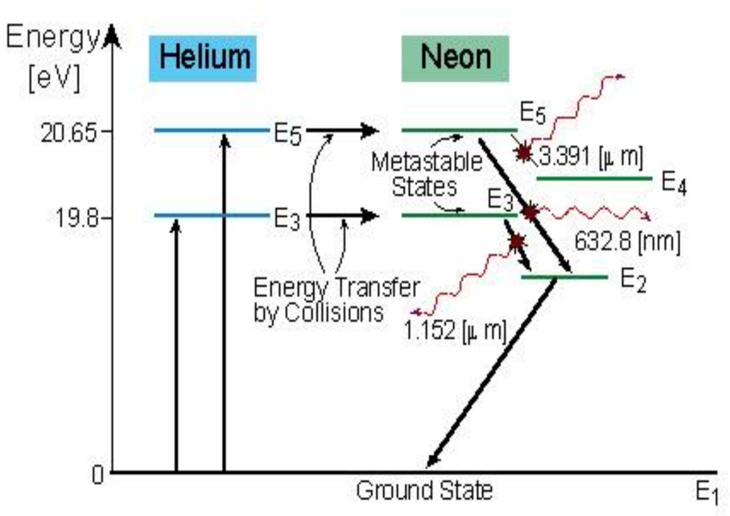
Gas Lasers (Examples: HeNe, Ar^+, Excimer, CO_2,..)

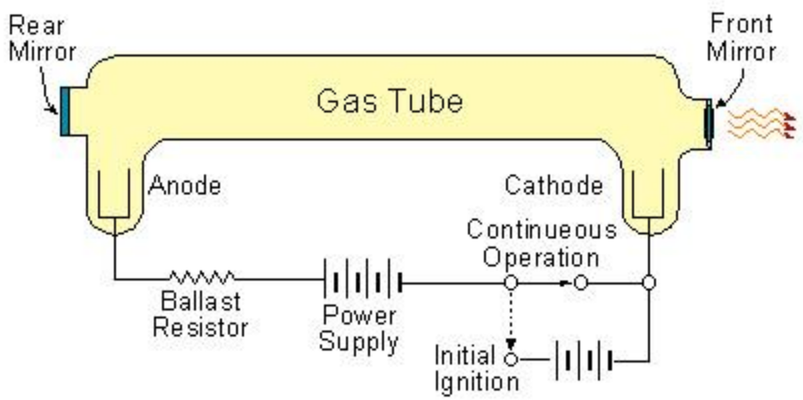


The excitation mechanism in most gas lasers is via *electric discharge*

The first Gas Laser: He-Ne

Ali Javan, et al. (Bell Labs, 1962)





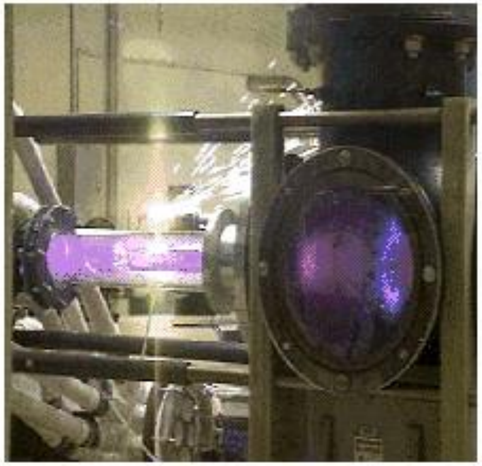
- The second working LASER system to be demonstrated.
- The first gas LASER to be produced.
- The first LASER to produce a continuous output beam
- The active laser medium is a gaseous mixture of He & Ne atoms, in a roughly 10:1 proportion
- The gas is enclosed in a cylindrical quartz DISCHARGE tube

Comparison of Gas Lasers

Laser Type	***Linear Power Density W/m***	***Maximum Power W***	***Power Efficiency %***
He-Ne	0.1	1	0.1
Argon	1-10	50	0.1
CO_2	60-80	$>10^4$	15-20

CO_2 Lasers (9-11 micron)

C. K. N. Patel, "Continuous-Wave Laser Action on Vibrational Rotational Transitions of CO2," Physics Review, Vol. 136 A, (Nov., 1964) P. 1187

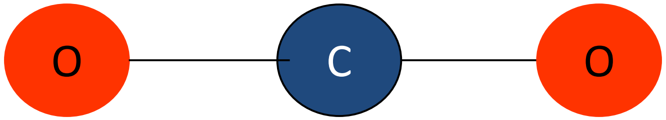


Applications (*pealing peanuts to star wars*)

- Industrial (cutting, welding, material processing)
- Military (range finding, targeting, remote sensing, sensor blinding, destroying …)
- Medical (cutting, skin resurfacing)
- …..

Molecular Vibrations and Rotations

•Transitions are between molecular vibrational-rotational levels.



Modes of vibrations:

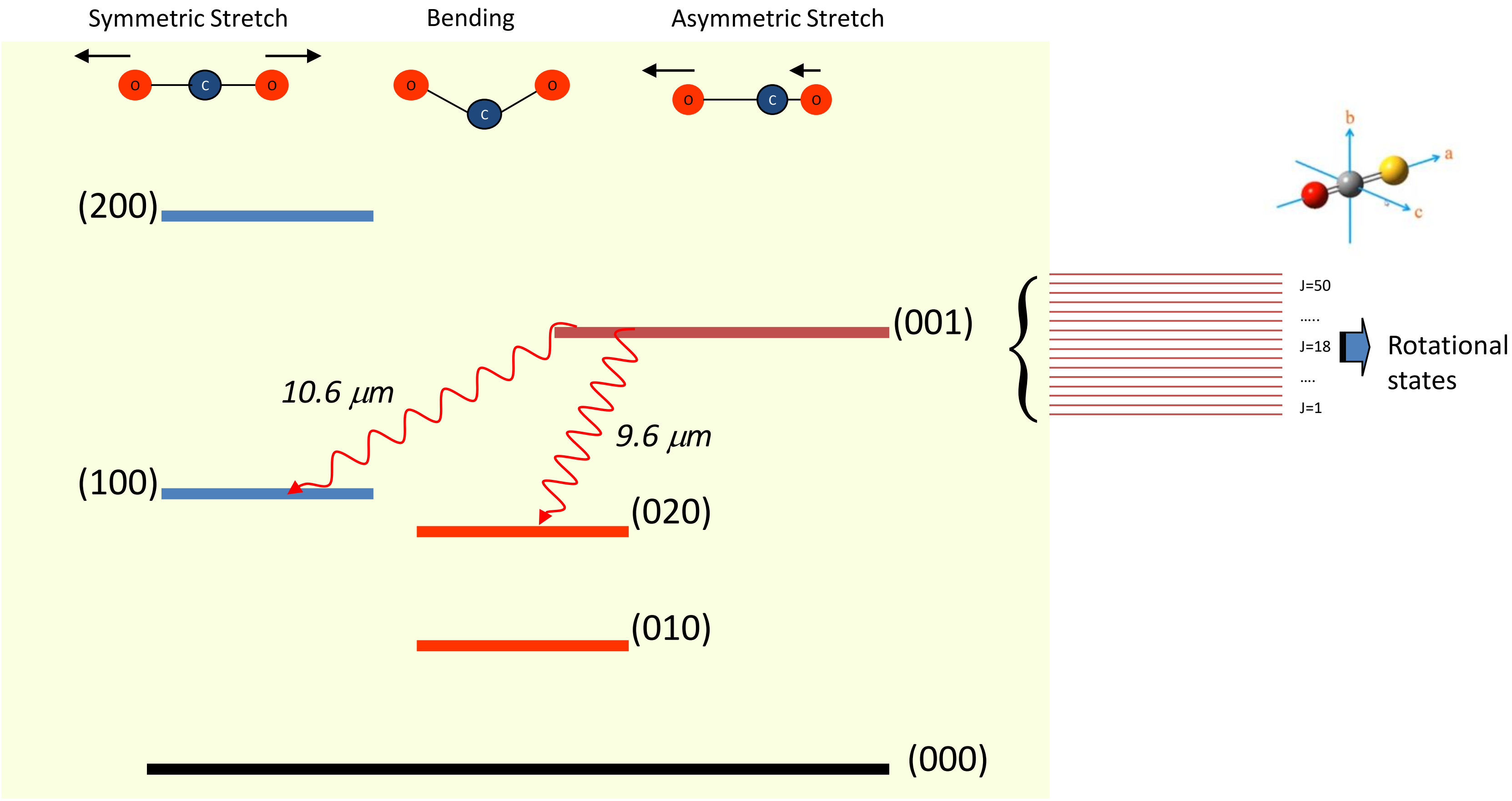
•Symmetric stretch

•Asymmetric stretch

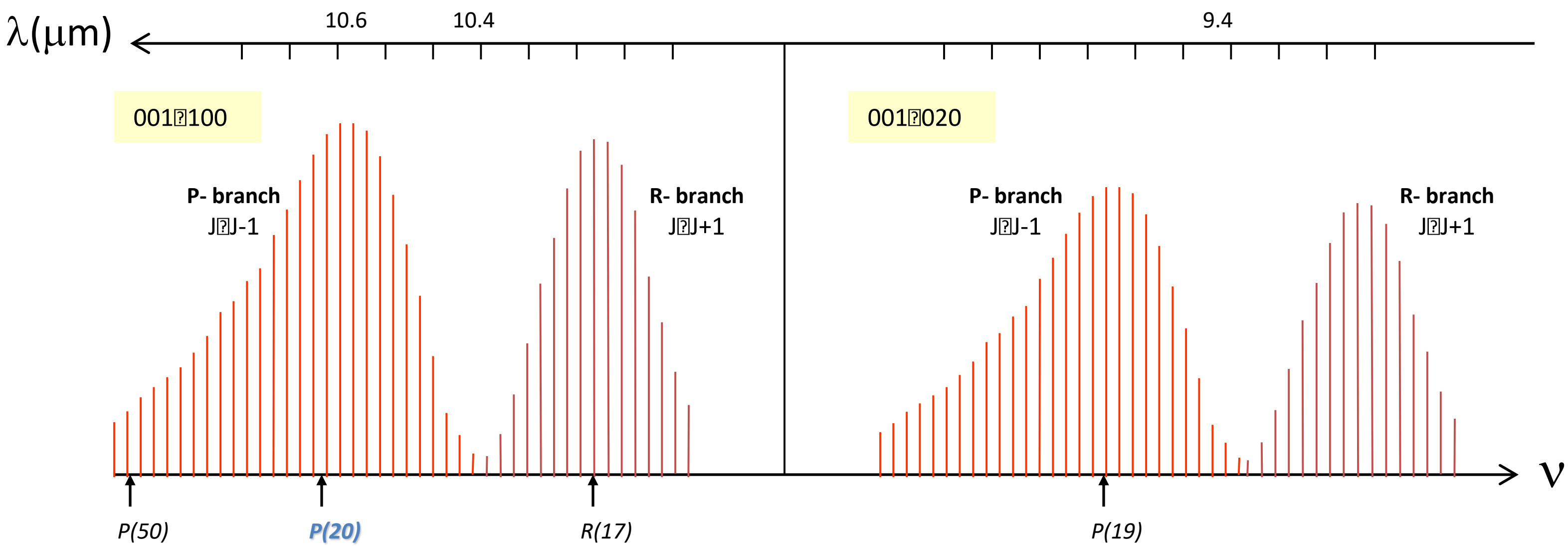
•Bending mode

Simple Harmonic Oscillator (Quantum Mechanics):

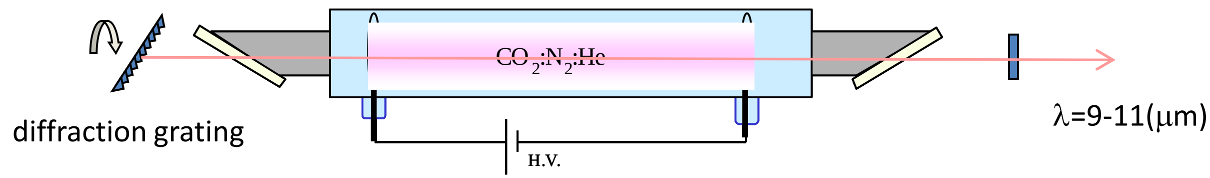
$$E(n_1,n_2,n_3)=h\nu_1(n_1+1/2)+h\nu_2(n_2+1/2)+h\nu_3(n_3+1/2)$$



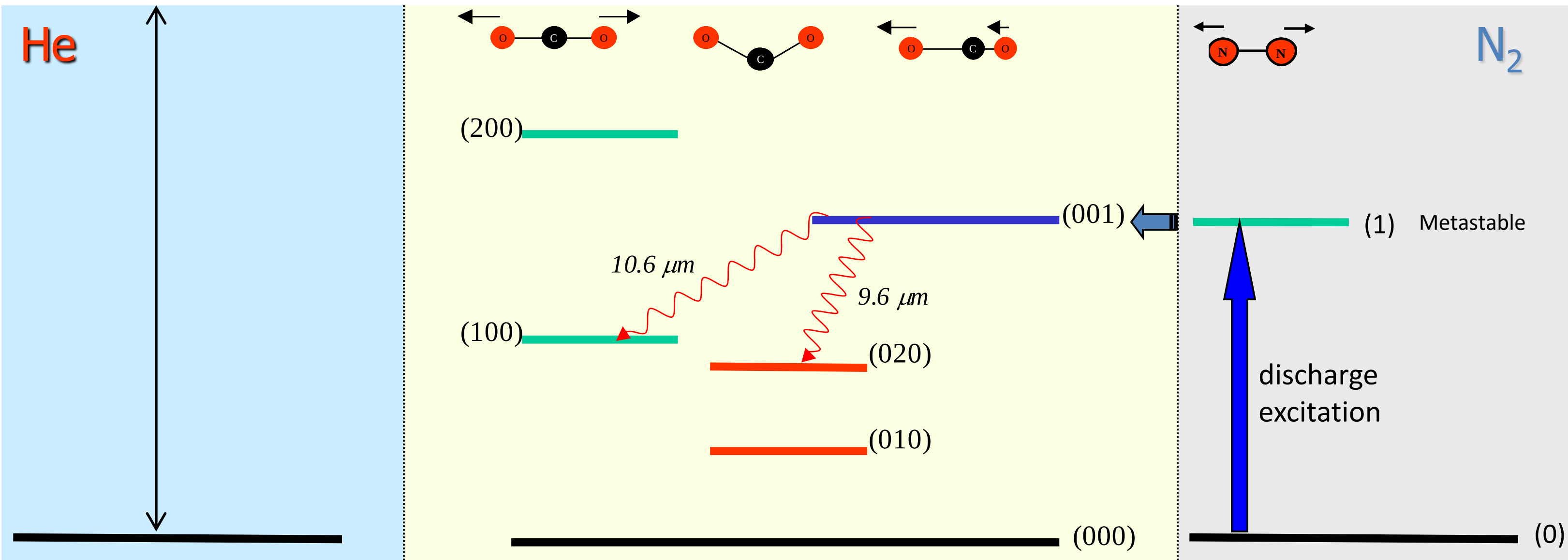
CO_2 Laser Transitions



Tuning:



Effect of Gas Mixtures: CO_2+N_2+He



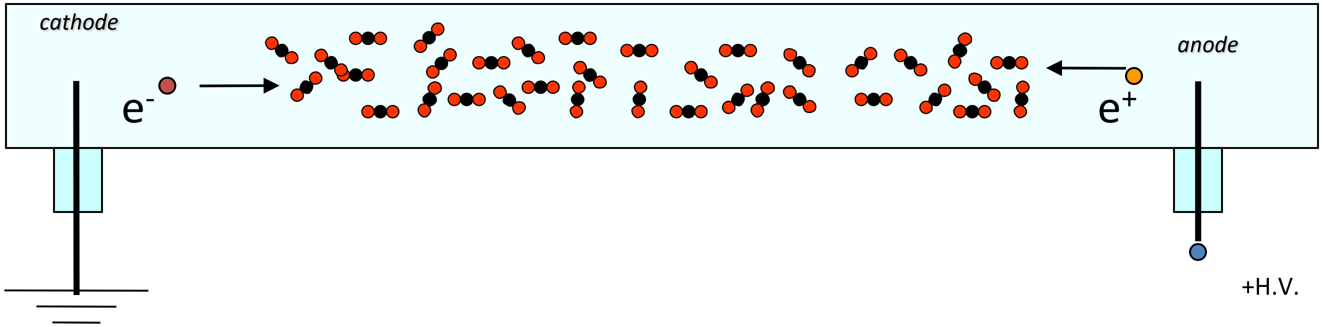
- Nitrogen helps populating the upper laser level in a discharge
- Helium helps to depopulate the lower laser level by collisions

Other possible additions to the gas mixture: CO, H_2

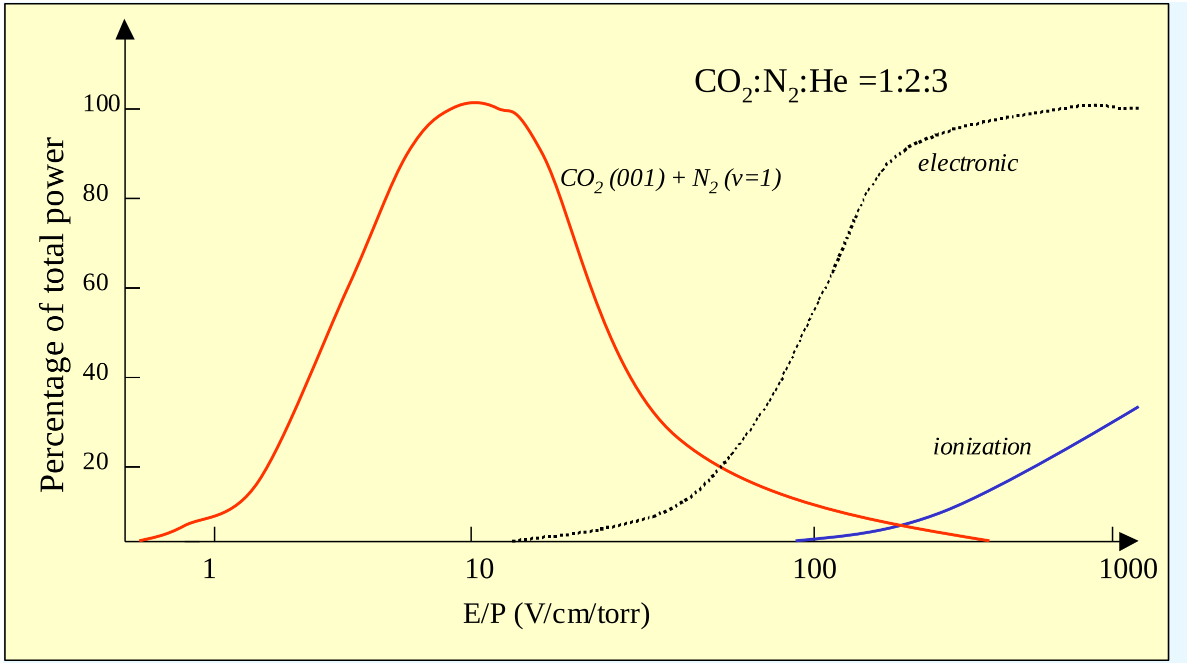
Typical Co_2:N_2:He Gas Ratios Recommended by Laser Manufacturers

CO_2	N_2	He	Laser Power Rating W
1	3	17	20
1	1.5	9.3	50
1	1.5	9.3	100
1	1.35	12.5	275
1	8	23	375
1	6.7	30	525
1	2.3	17	1000

11.3 Gas Discharge Phenomena



- Electrons emitted from cathode get accelerated by the electric field
- The energetic electrons excite the vibrational modes of the gas molecule via inelastic collisions



Example:

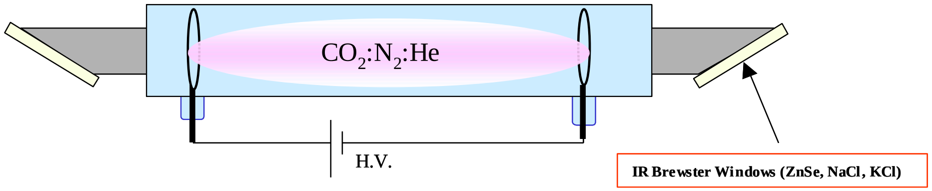
L=1 meter and P=25 torr

Need V=25 kV for optimum operation

11.4 Specific Types of CO_2 Lasers

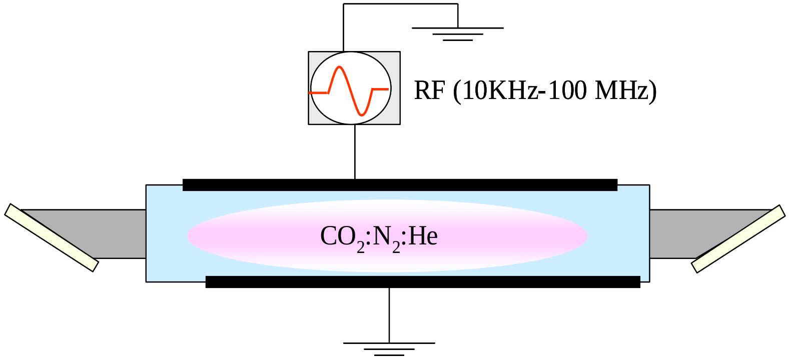
High Power CW Operation

❑ DC-Discharge



- Longitudinal discharge (High Voltage: 10-100 kV)
- Pressure: 10-100 torr
- Multistage discharge tubes can be used to produce kilowatts of output power

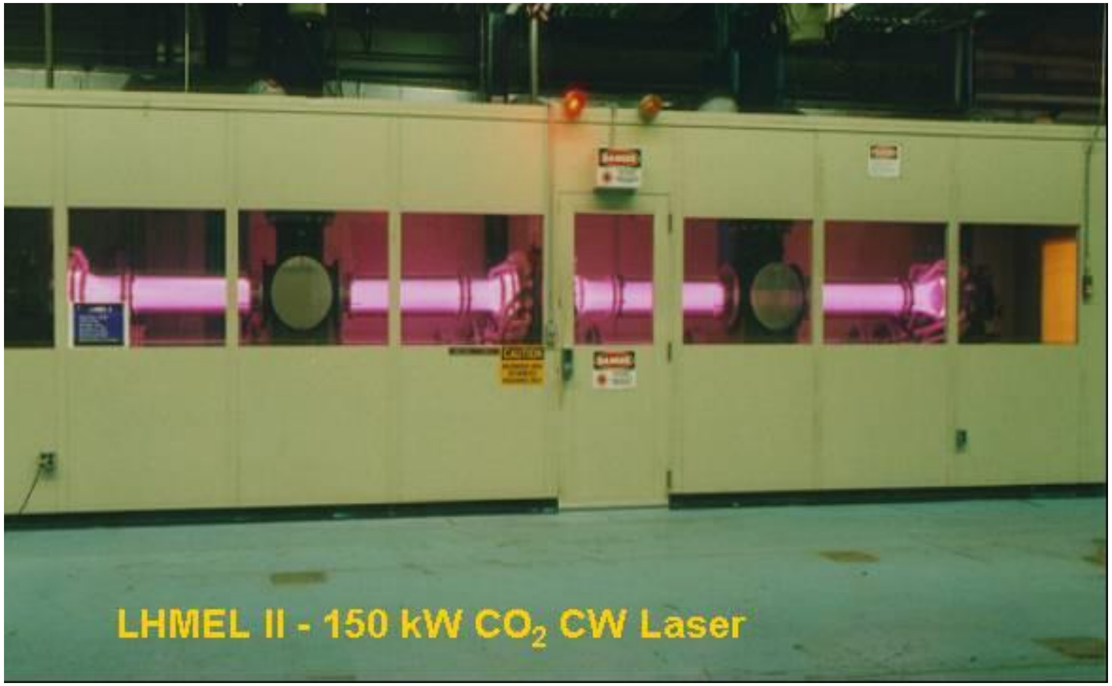
❑ RF-Discharge

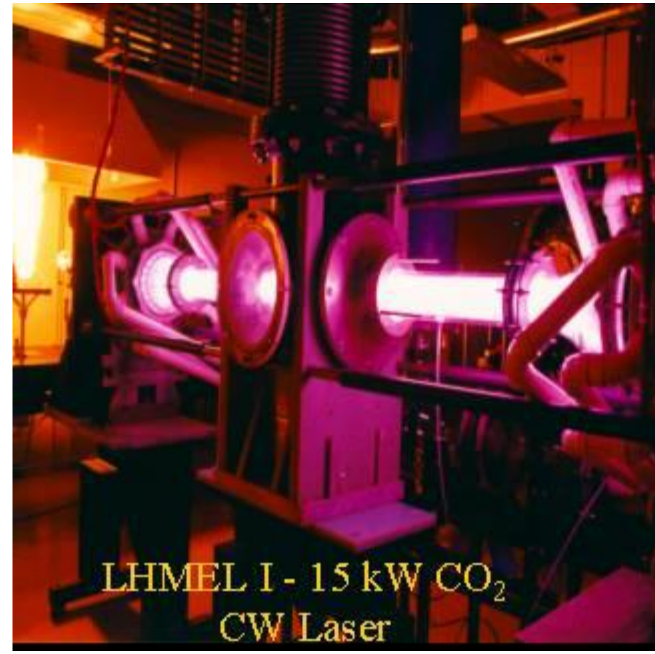


- In practice waveguides are used.
- High discharge stability, high pulsing frequency (up to 100 kHz)
- Expensive RF generator and requires EMI shielding

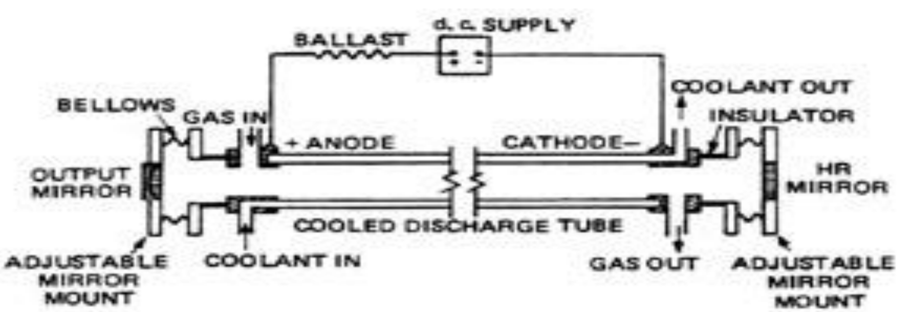
0.2 W/cm in a waveguide laser

Laser Hardened Materials Evaluation Laboratory (LHMEL)
WP-AFB, Dayton, OHIO





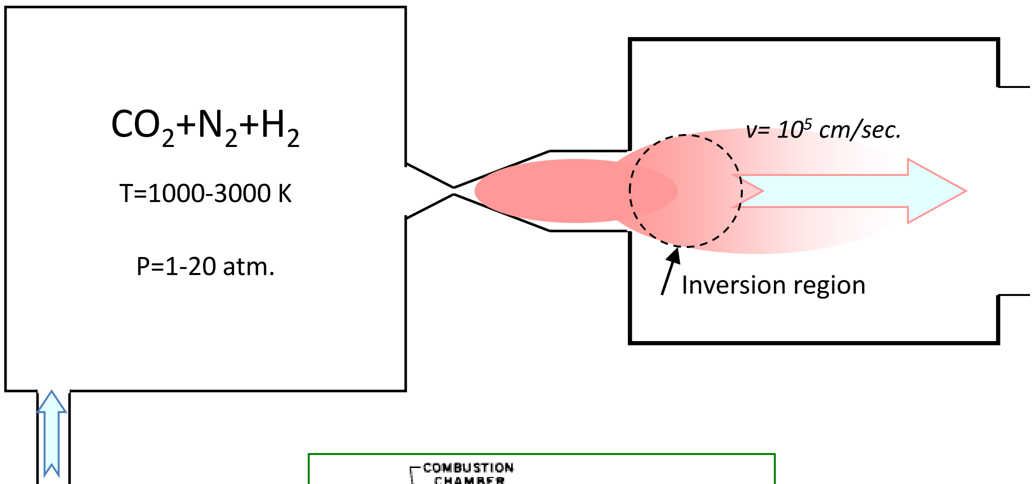
Electric Discharge Coaxial Laser (EDCL)

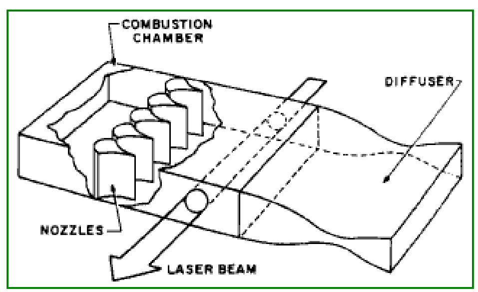


❑ Gas-Dynamic Lasers

Basov & Oraevskii (1963)

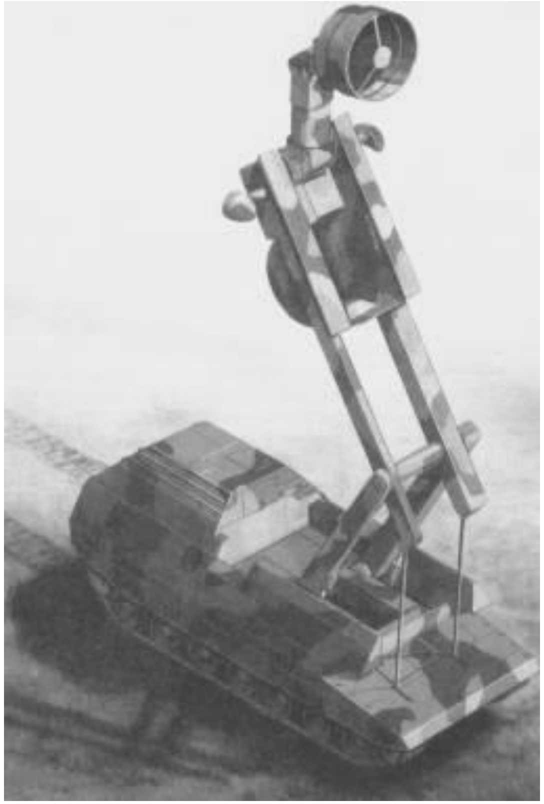
Principle: *Population inversion by rapid expansion (supersonic flow) of a super-heated gas*





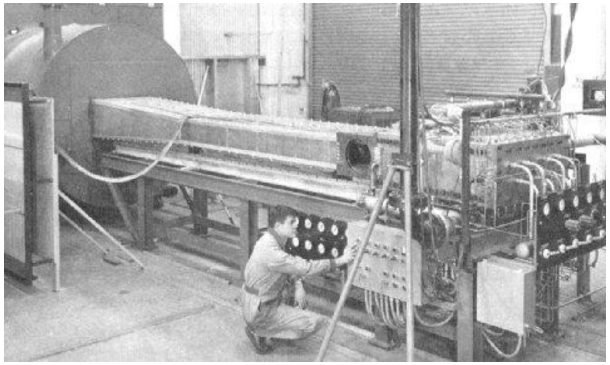
• cw powers up to 1 MW have been obtained from gas-dynamic CO_2 lasers !!

Gas-Dynamic Lasers

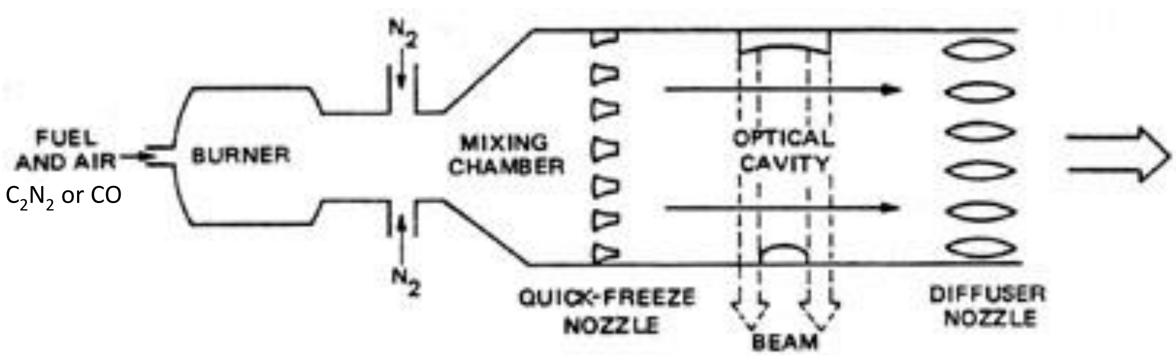


HELEX

High Energy Laser Experimental
Germany, 1970's

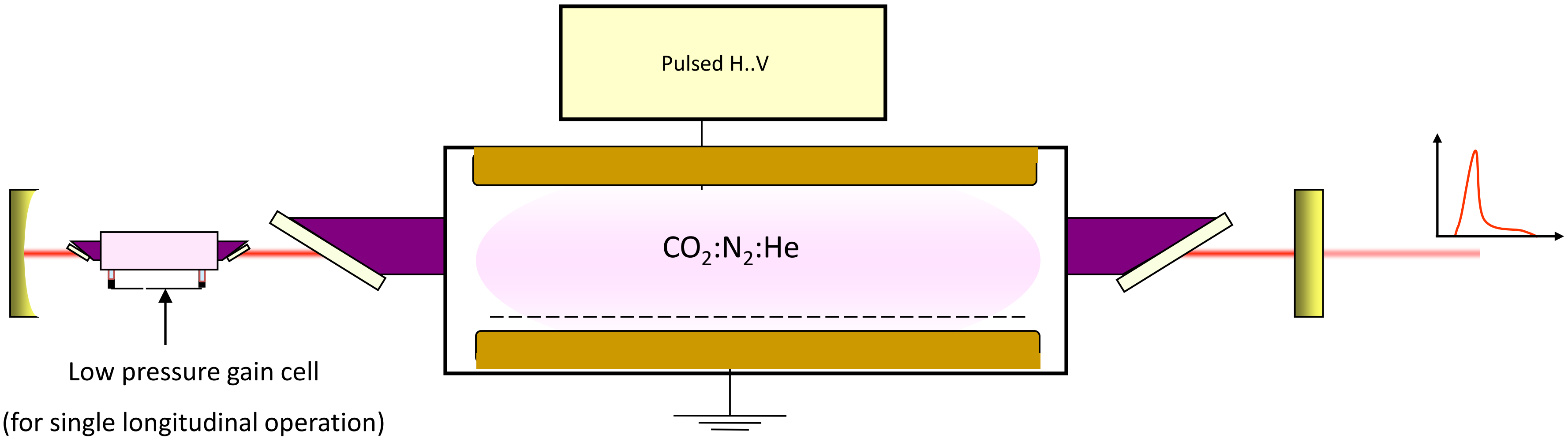


Large scale 135 Kilowatt gasdynamic laser at Avco Everett Research Lab.



•Pulsed CO_2 Lasers

Most Common: Transversely Excited Atmospheric (**TEA**) CO_2 Lasers

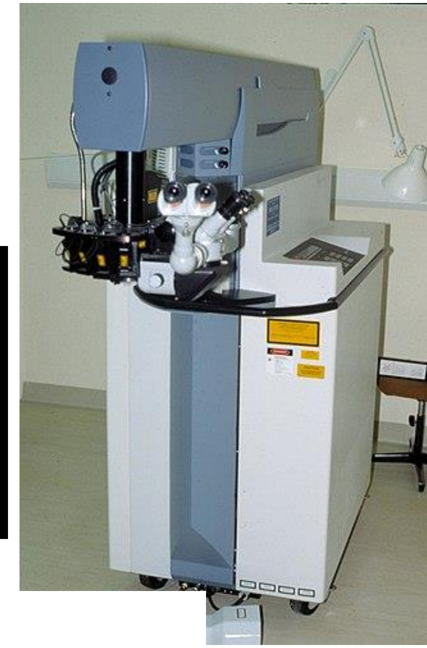


- Flowing or sealed systems
- Pulsewidths from 50 ns to 300 ns
- Repetition rates: 1Hz. to 1 kHz.
- Pulse energy: 50 mJ to 10 J (amplified)

Excimer (Exciplex) Lasers

Nikolai Basov*, V. A. Danilychev and Yu. M. Popov, at the Lebedev Physical Institute

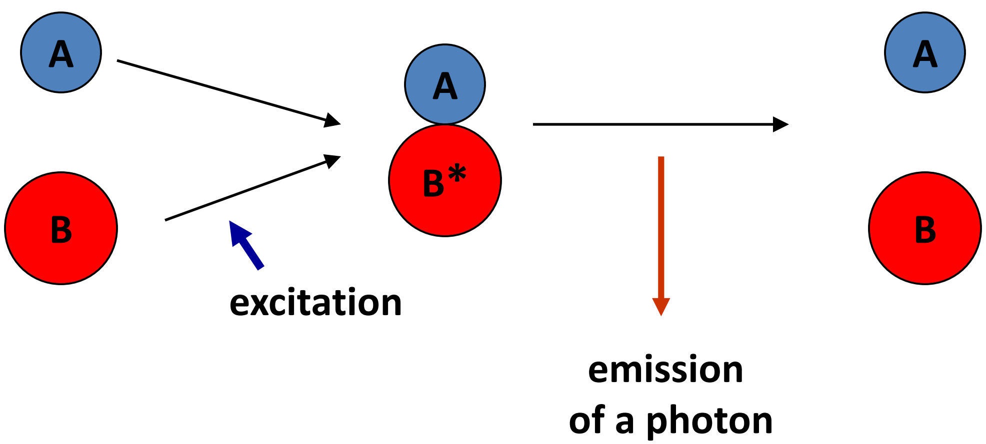
Applications: lithography, micromachining and eye surgery

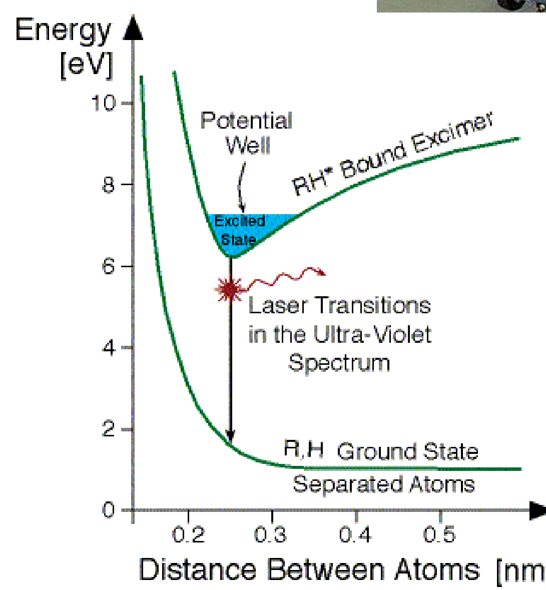


Molecules exist only in the excited state
(**Excimer=**Excited-Dimer) or (**Exciplex= Exciated-Complex)**

$XeCl^*$ 308 nm
KrF^* 248 nm
ArF^* 193 nm
F_{2*} 156 nm

Pulsed, Typically 10-50 ns, 5-20 mJ





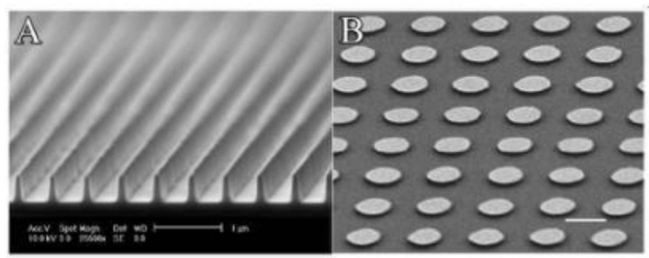
Nobel Prize, Physics (1964), Shared with Townes and Prokhorov

Excimer Lasers

Eye surgery

Lithography

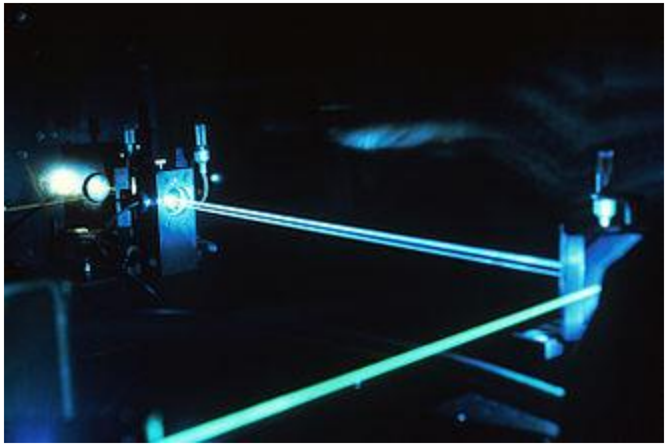
(Cymer Inc.)



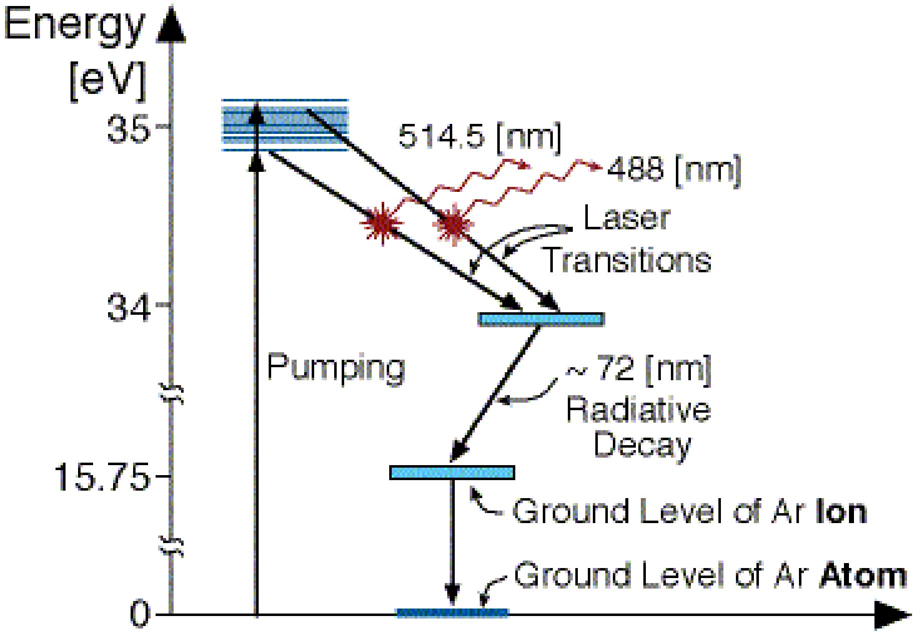
(www.spie.org)

Argon Ion Laser

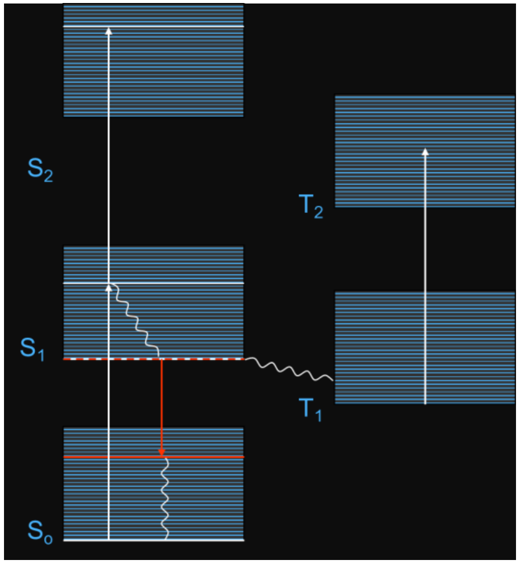
488 and 514 nm

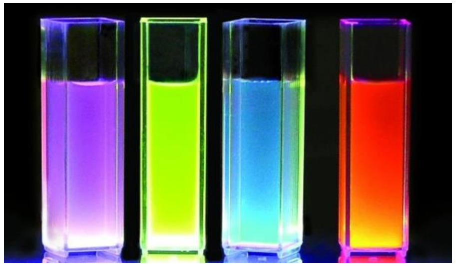


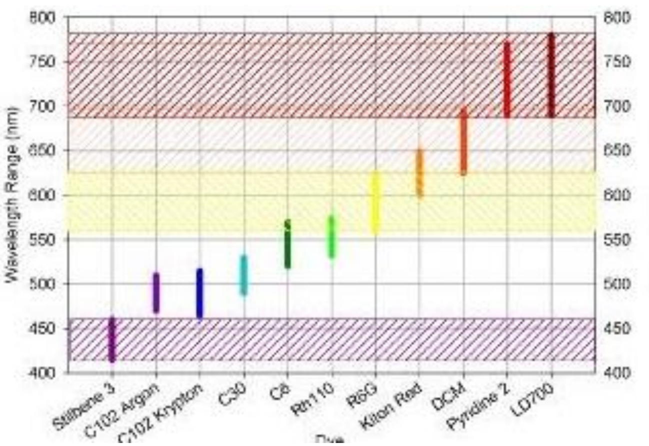
Ar^+



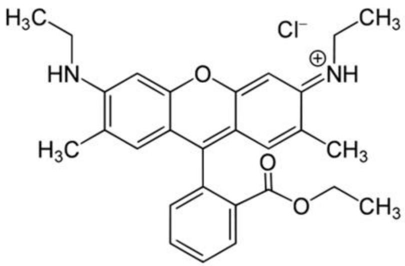
Organic Dye Lasers

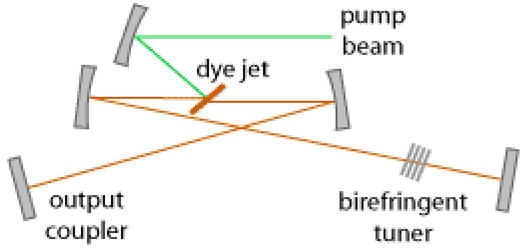


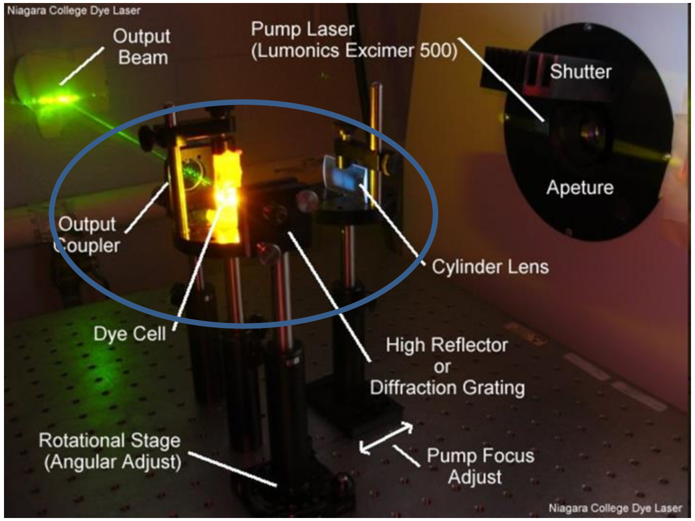




Example: Rhodamine 6G

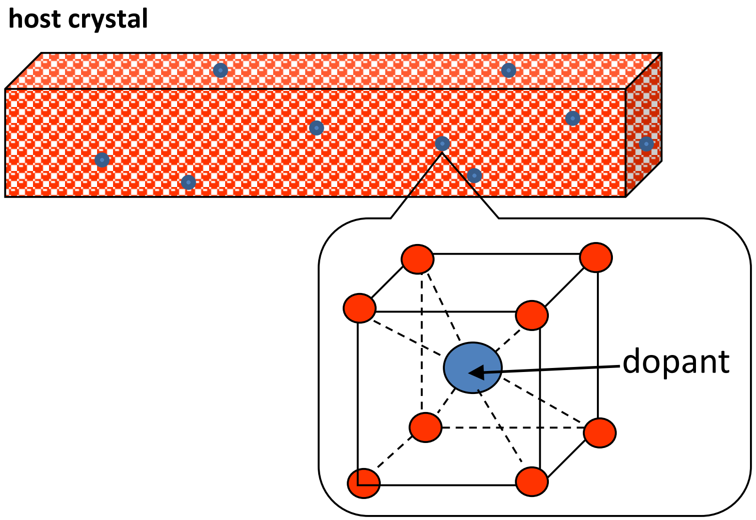


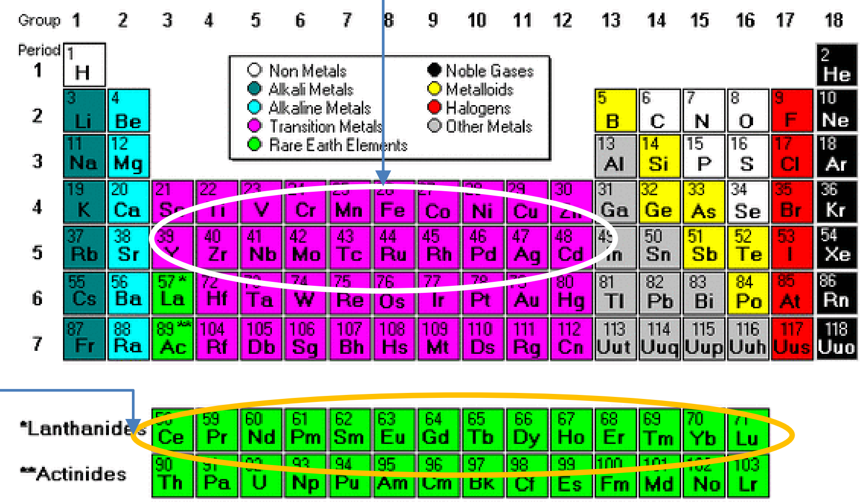




Solid-State Lasers

- The lasing atoms (ions) are fixed in a solid (crystal, glass).
- Solid-state lasers can operate in continuous (cw) or various pulsed modes.
- The active ions are most commonly either a **rare-earth** or **transition metal** elements





Examples:

(a) Nd^{3+} :YAG λ = 1.064 μm, 1.331 μm

(b) Nd^{3+} :glass λ = 1.062 μm (silicate glass), λ = 1.080 μm (fused silica)

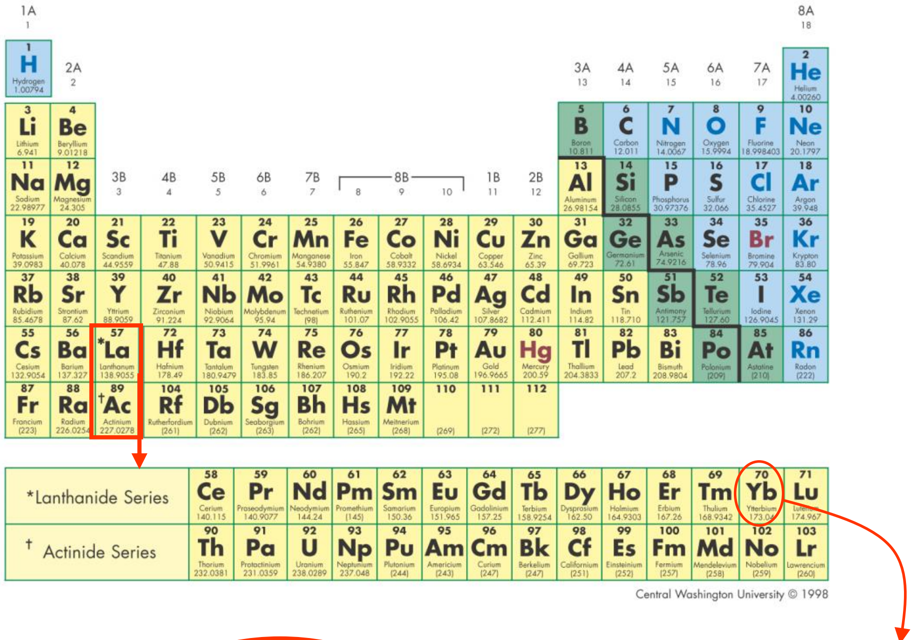
(d) Hm^{3+} :YAG, Tm^{3+} :YAG λ = 2.1 μm

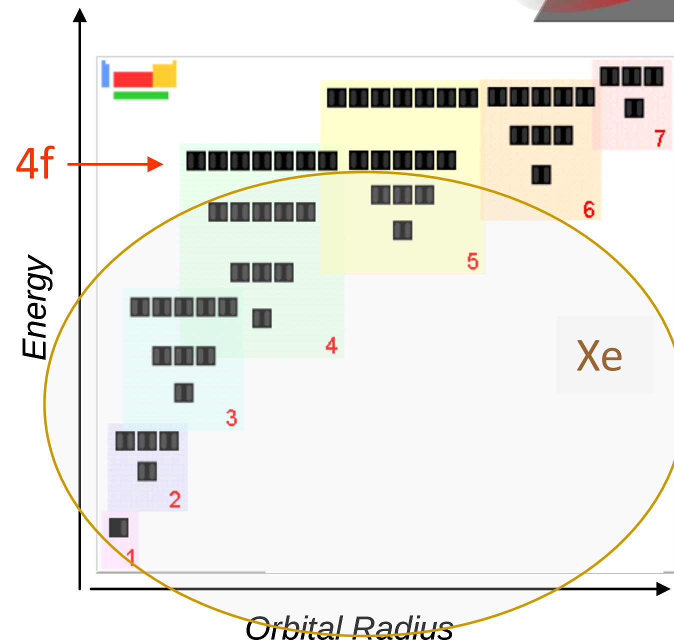
(e) Yb^{3+} : YAG, λ = 1.03-1.05 μm

(f) Ti^{3+} :sapphire, λ = 0.7 - 1.1 μm

(g) Fe^{2+} :ZnSe λ = 3.7 – 5.5 μm

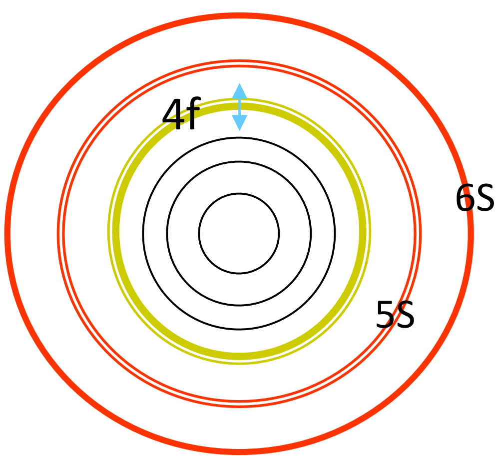
The 4f-4f transitions in Rare-Earths Ions:

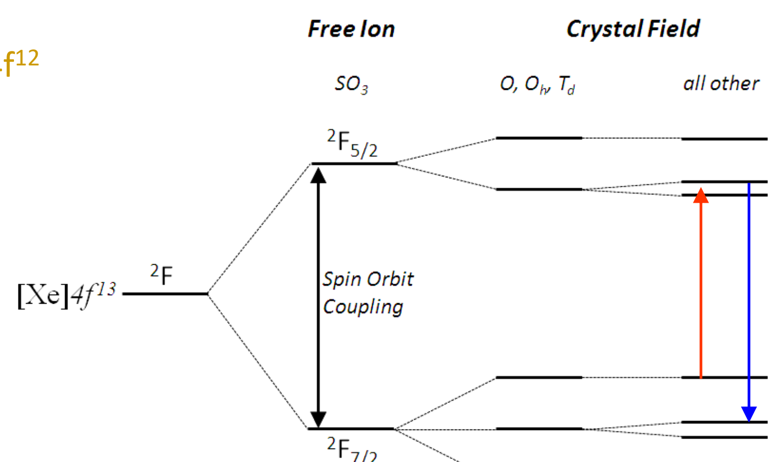




Yb ➡ $(Xe)4f^{13}6s^{2}$

$Yb^{3+} = (Xe)4f^{12}$





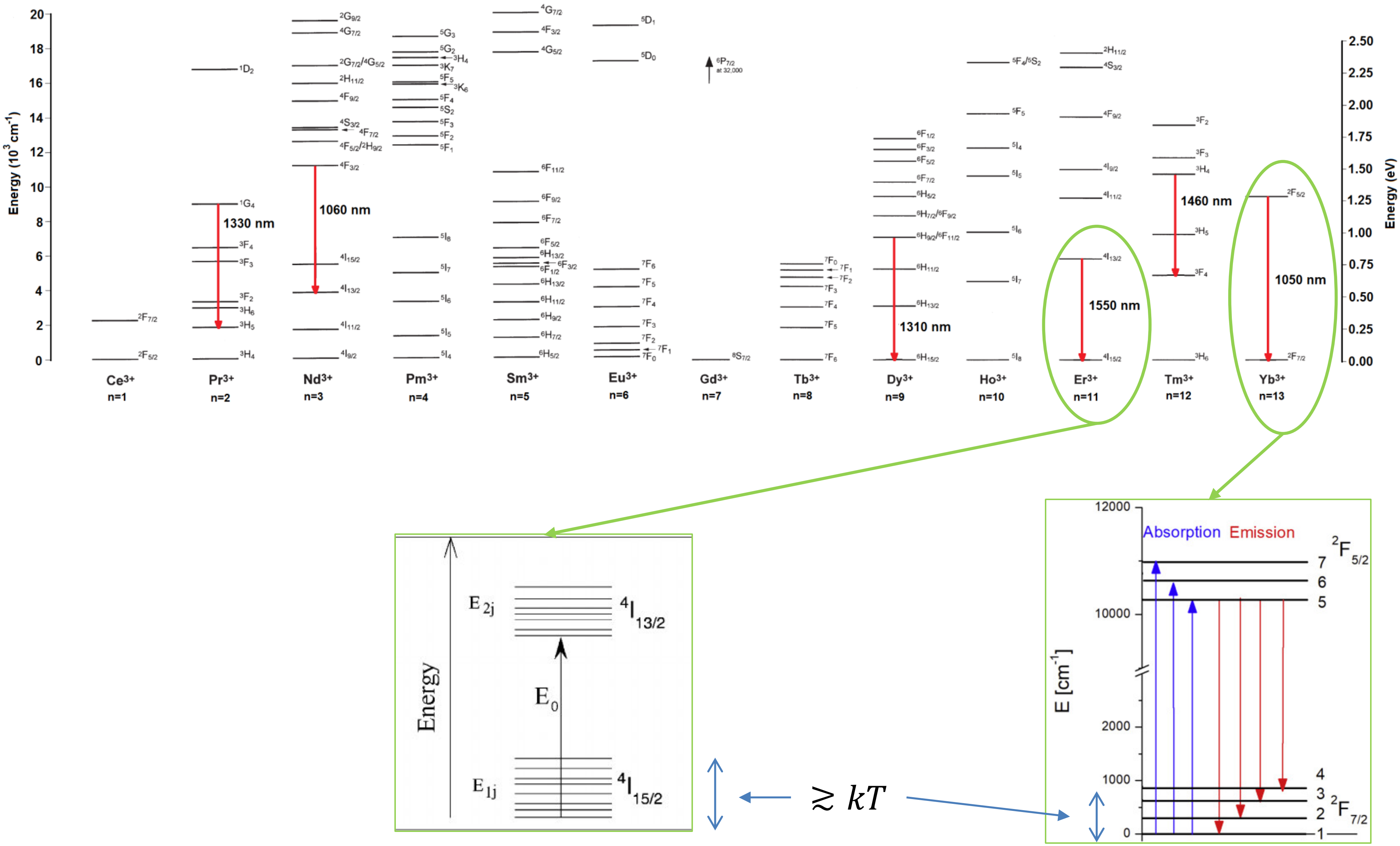
Letter	S	P	D	F	G	H	I
L	0	1	2	3	4	5	6

$$^{2S+1}L_J$$

Degeneracy: $g = 2J + 1$

Rare-Earth Ion Doped Lasers

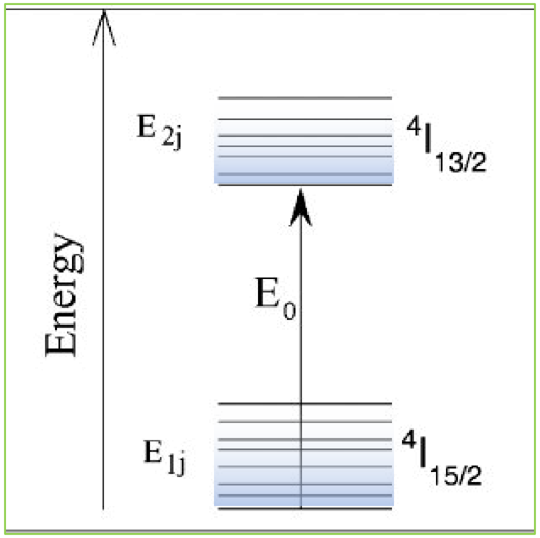
Lanthanides



Quasi Four-Level Lasers

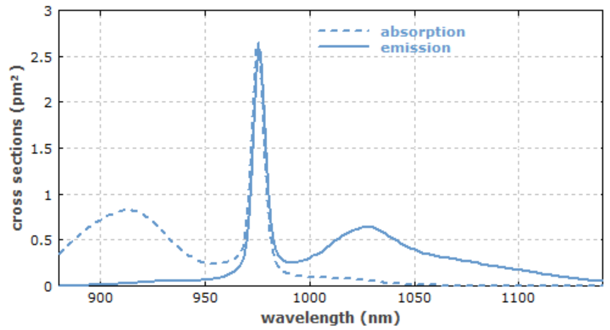
McCumber Relation

D. E. McCumber, "Einstein relations connecting broadband emission and absorption spectra", Phys. Rev. 136 (4A), A954 (1964),

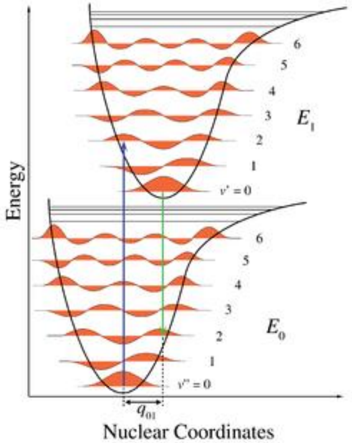


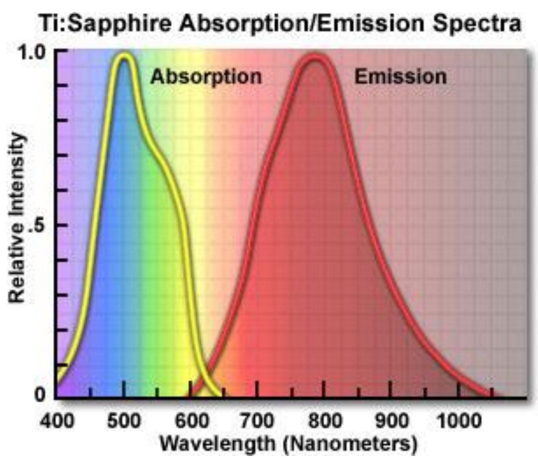
$$\sigma_{abs}(\nu) = \sigma_{em}(\nu)\exp\left(\frac{h\nu - E_0}{k_B T}\right)$$

Yb-doped germanosilicate glass

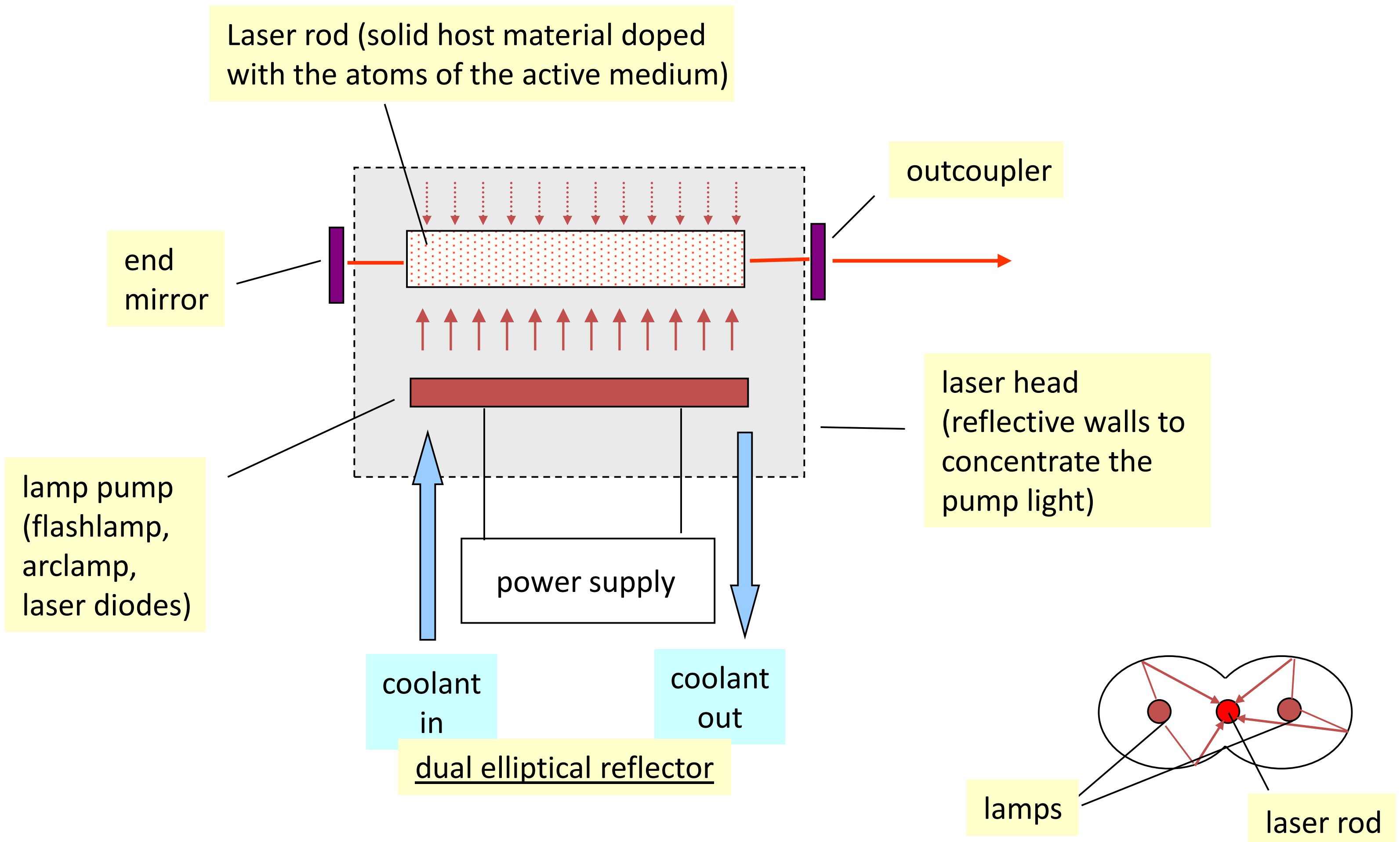


Vibronic Transitions

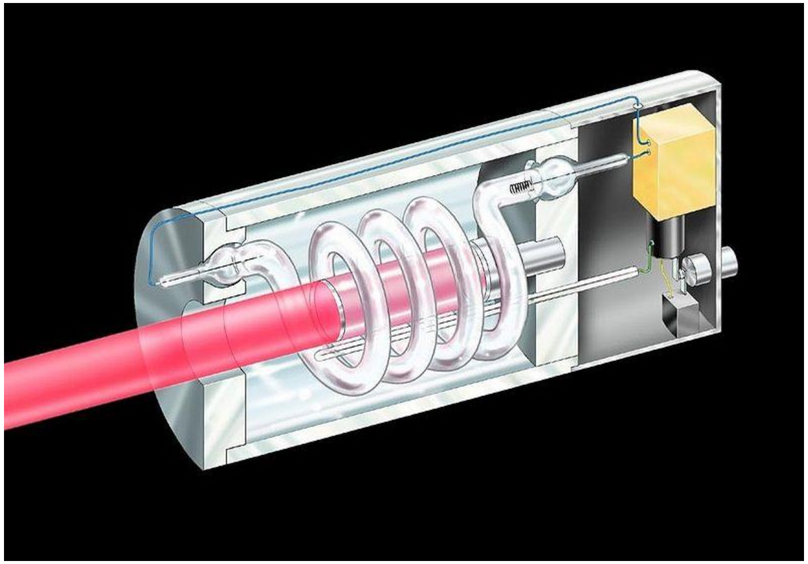


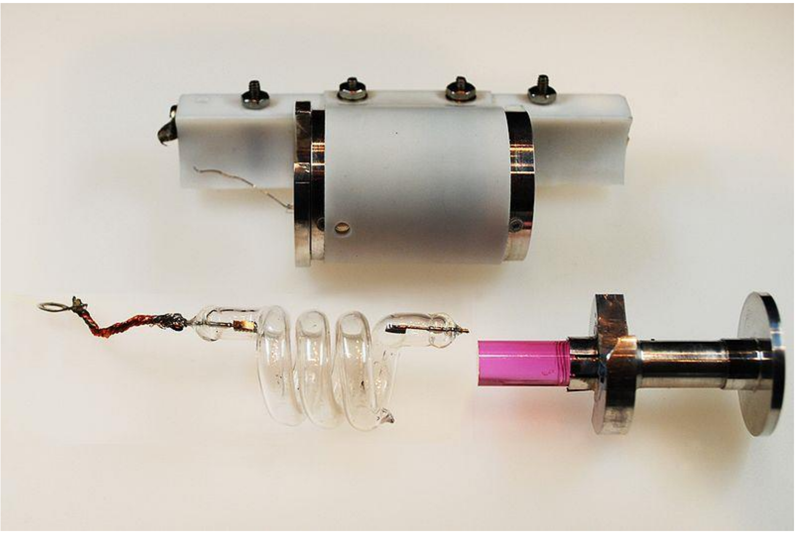


Layout of early (flash-lamp or arc-lamp pumped) solid-state lasers



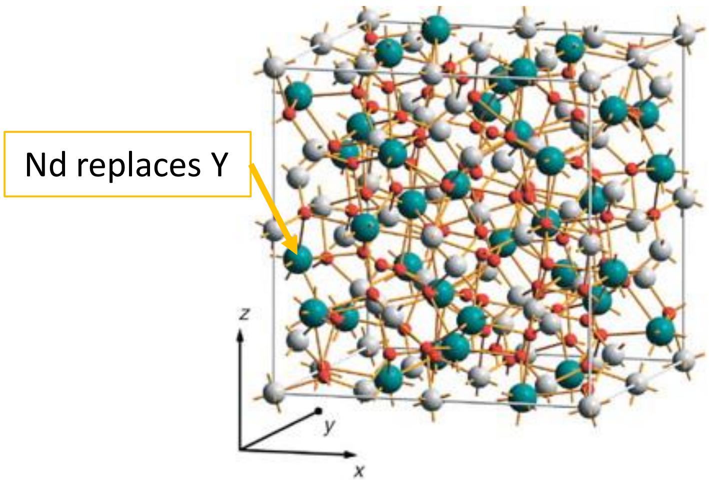
Maiman’s Ruby Laser



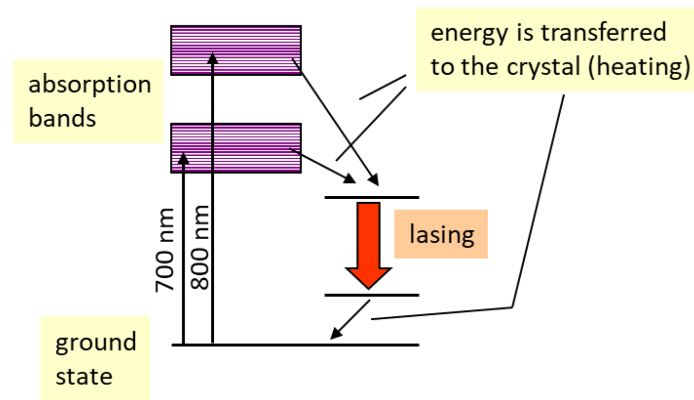


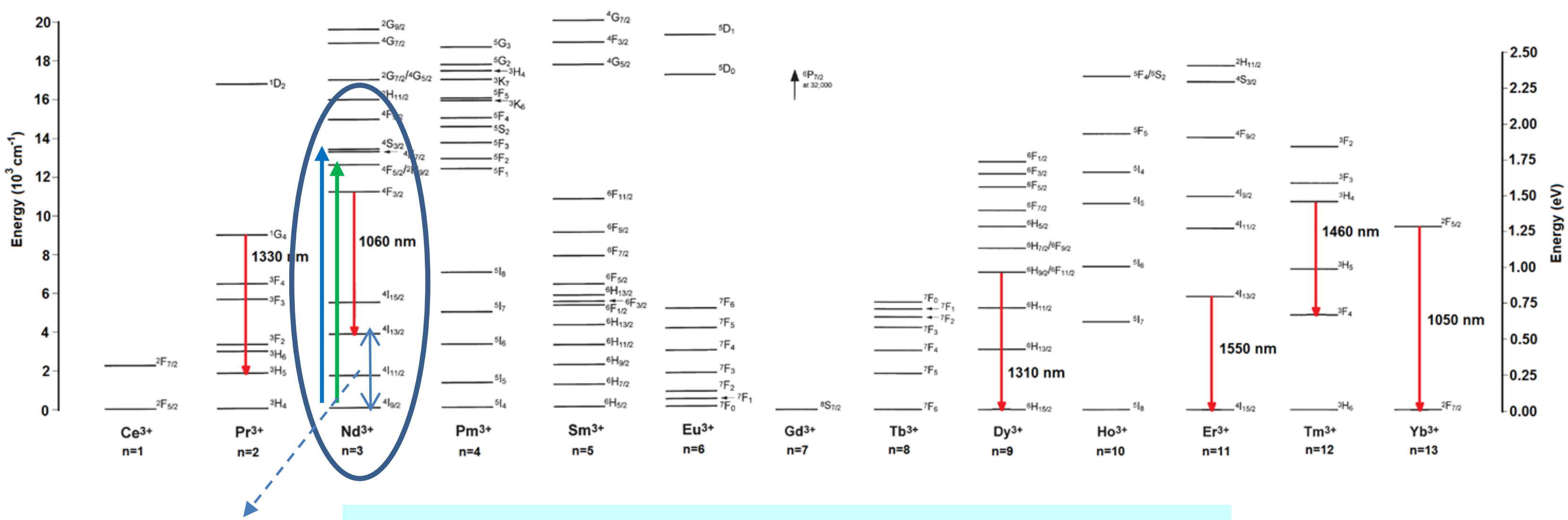
Example: Nd:YAG laser

YAG: Yttrium Aluminum Garnet **($Y_3Al_5O_{12}$)**



Energy diagram of Nd^{3+}:





$\gg kT$

Output (Nd:YAG, Nd:YLF, Nd: YVO_4)

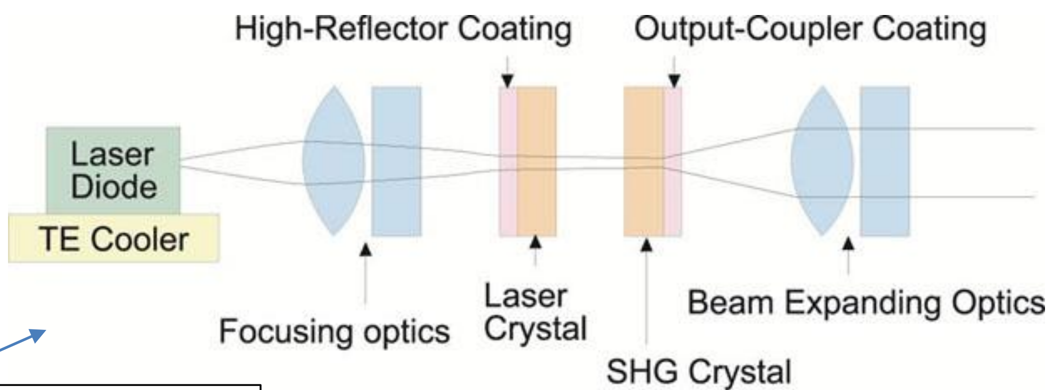
cw: $\leq$ 1000 W

pulsed: pulse energy $\leq$ 1 Joule

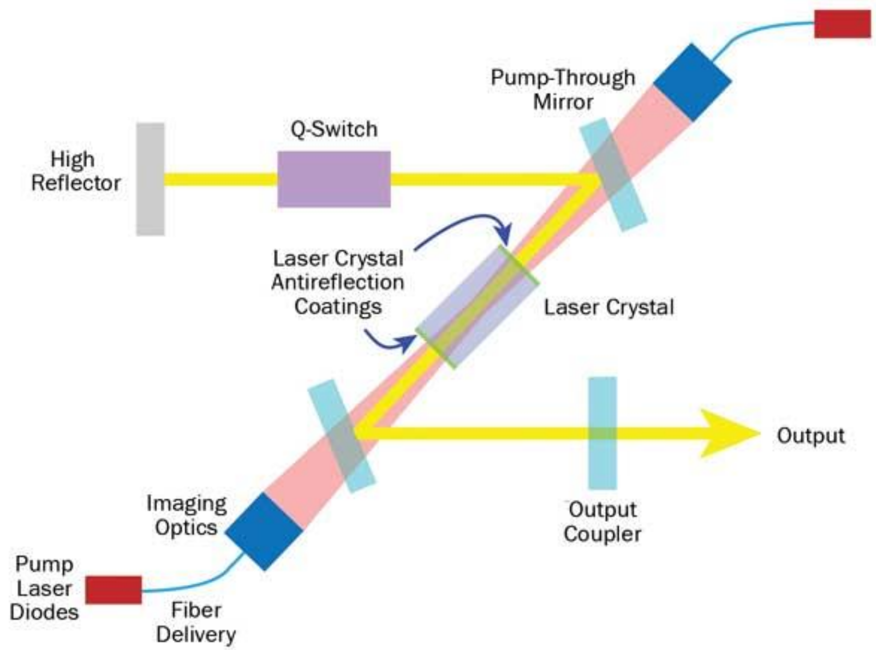
Q-switched – 5-20 ns pulse duration

modelocked – 10-100 ps pulse duration

DPSS : Diode-Pumped Solid-State Laser

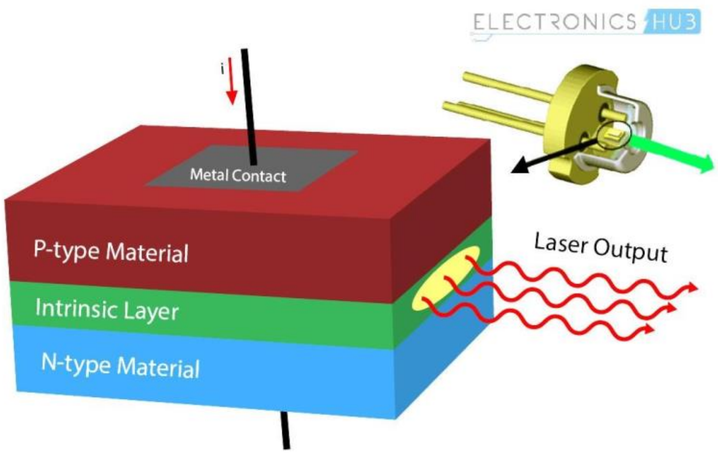


Similar to one used in our Optics Lab



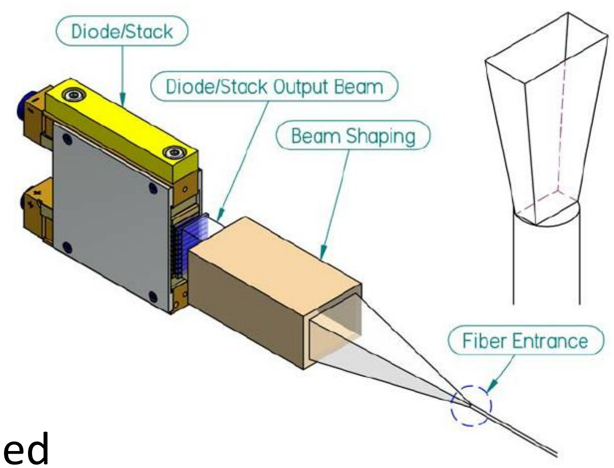
Diode Lasers for Pumping

Semiconductor lasers will be covered in more detail (next lecture)



LASER DIODE CONSTRUCTION

- Efficient (current injection)
- High power
- Designer Wavelength
- Poor Beam Quality
- Broadband (3-5 nm)



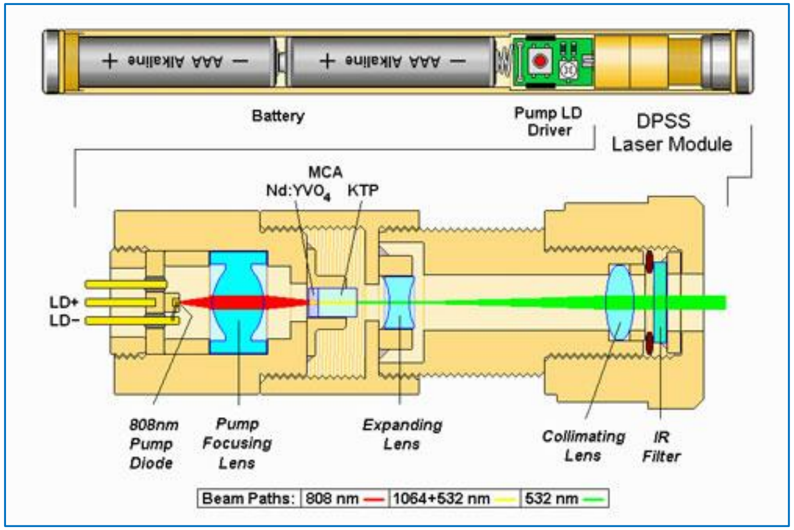
High Power (Diode Bar) Fiber Coupled

DPSS : Diode-Pumped Solid-State Laser

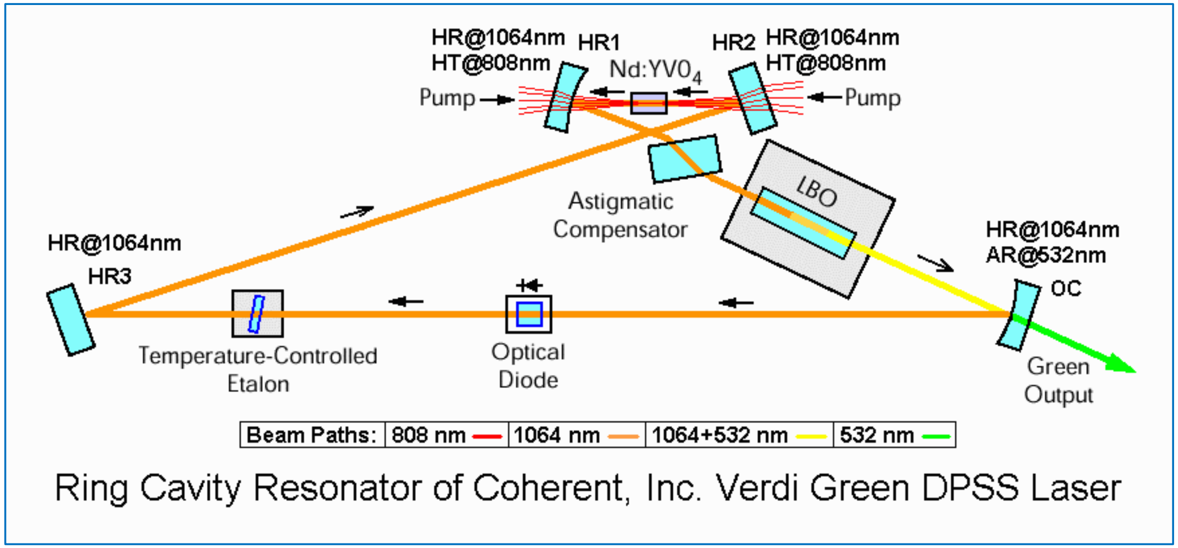
Example $Nd:YVO_4$ (Vanadate)

From laser pointers (5-10 mW) to 100W lasers

5-10mW
$20



5-10W
$10k-$40k



Titanium doped sapphire ($Ti^{3+}:Al2O3$) laser

The jewel of ultrafast lasers

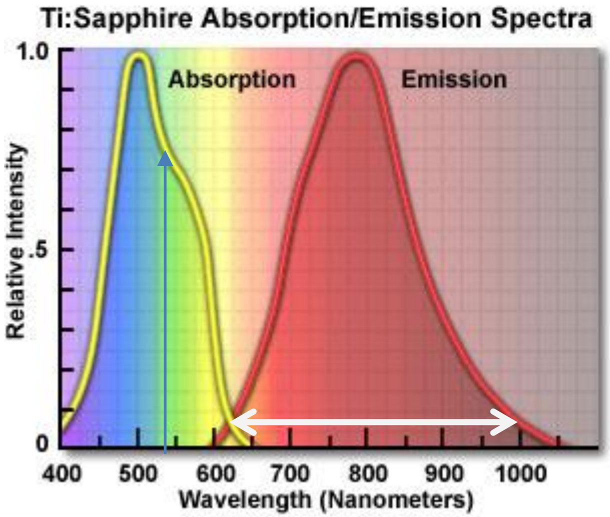
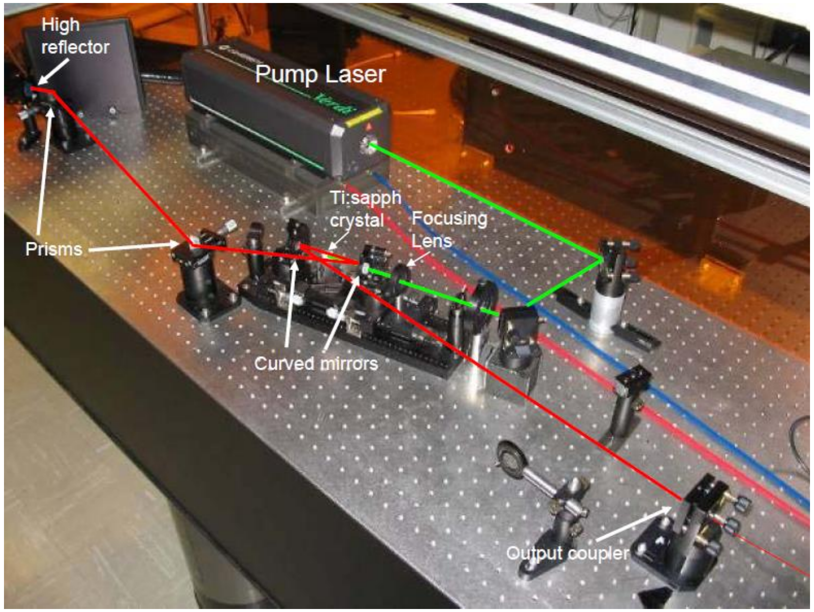
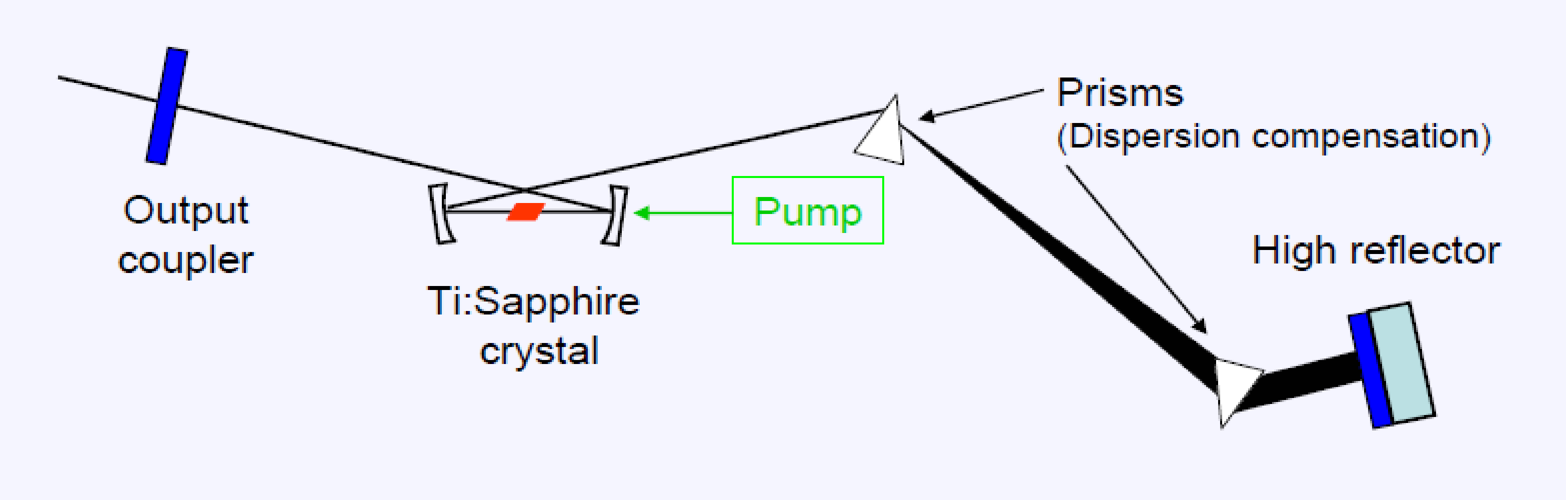


Figure 1





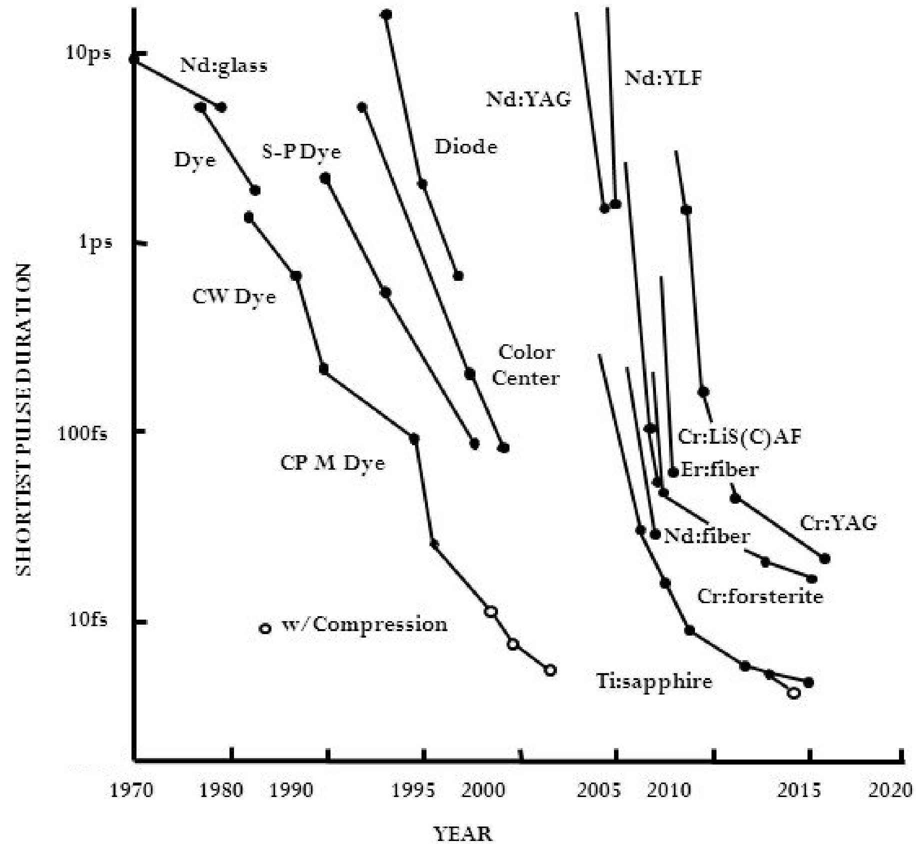
Historical Progress in Ultrashort Pulses

Nobel Prizes

John L. Hall and Theodor W. Hänsch“
“for their contribution to the development of laser-based precision spectroscopy, including the optical frequency comb technique” (2005)

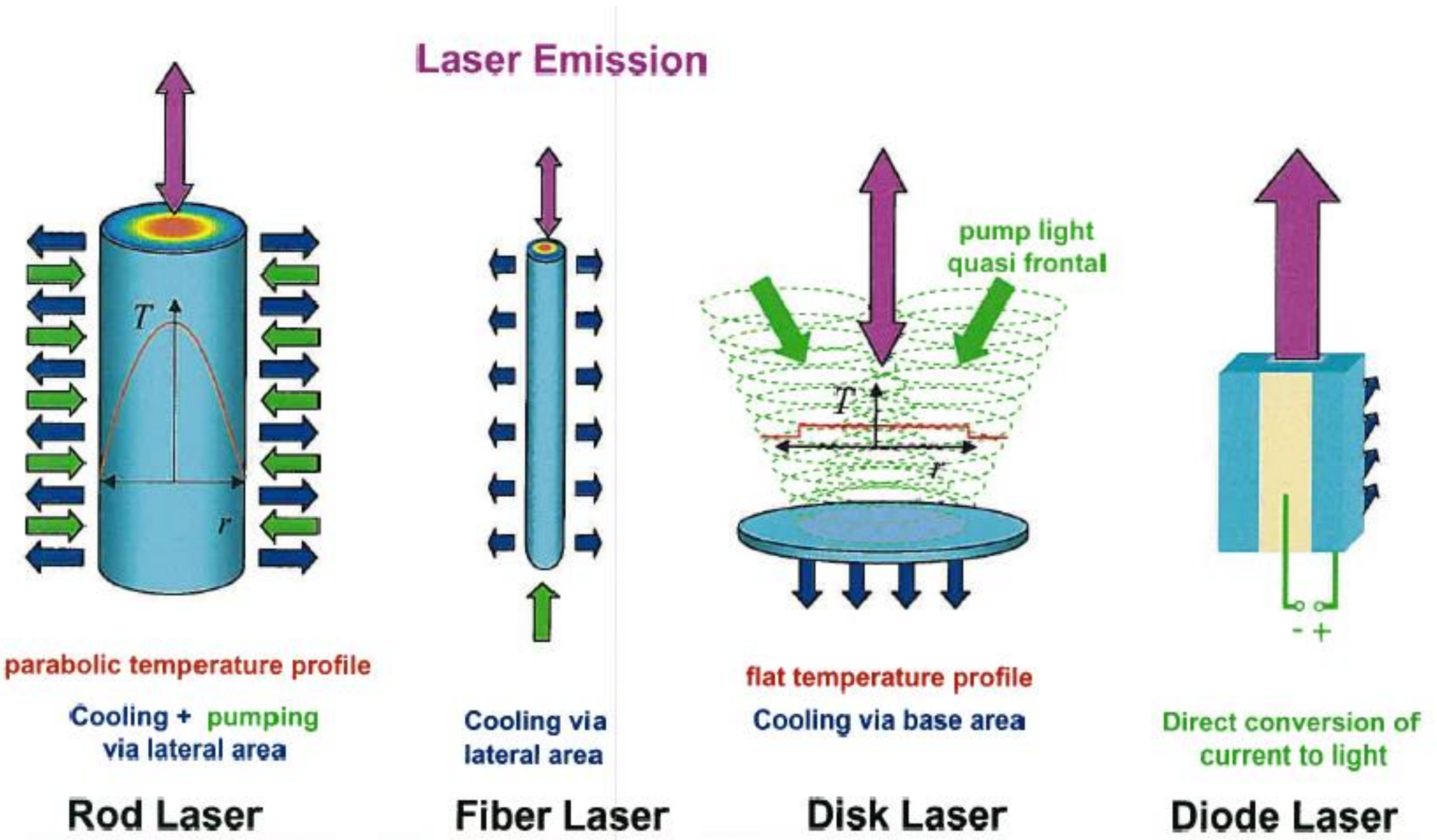
Gérard Mourou and Donna Strickland
“for their method of generating high-intensity, ultra-short optical pulses” 2018

Ahmed H. Zewail ”for his studies of the transition states of chemical reactions using femtosecond spectroscopy” 1999 (Chemistry)

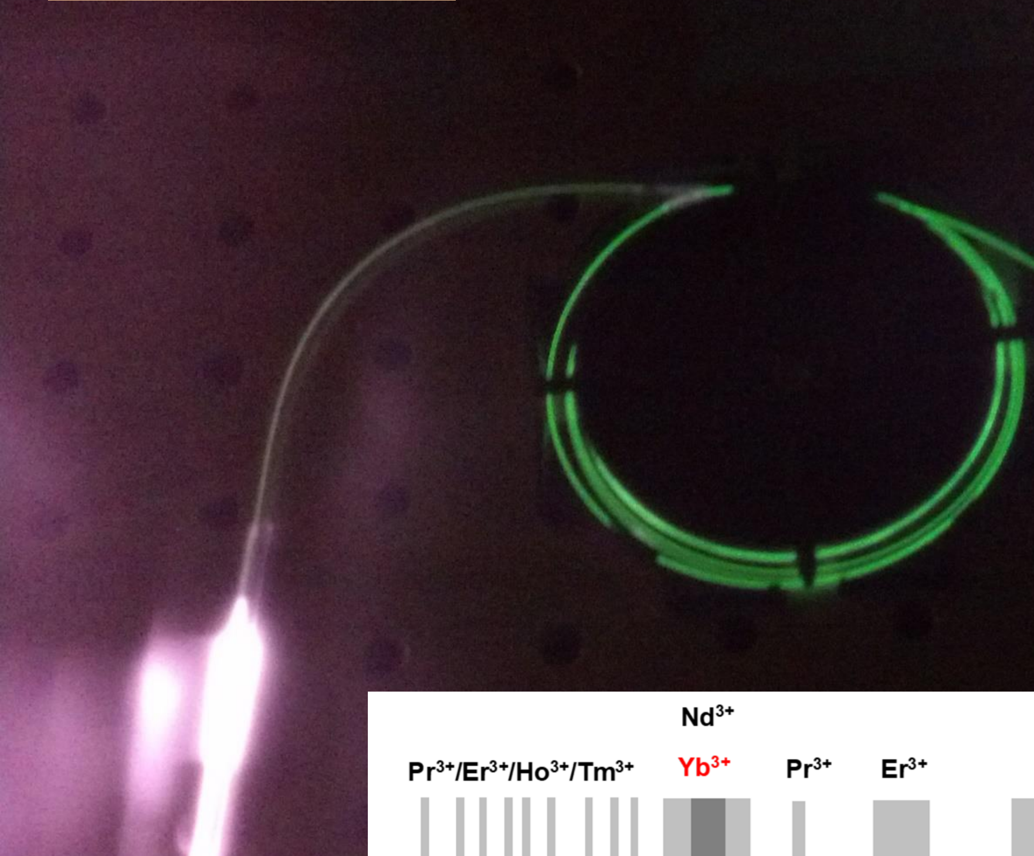


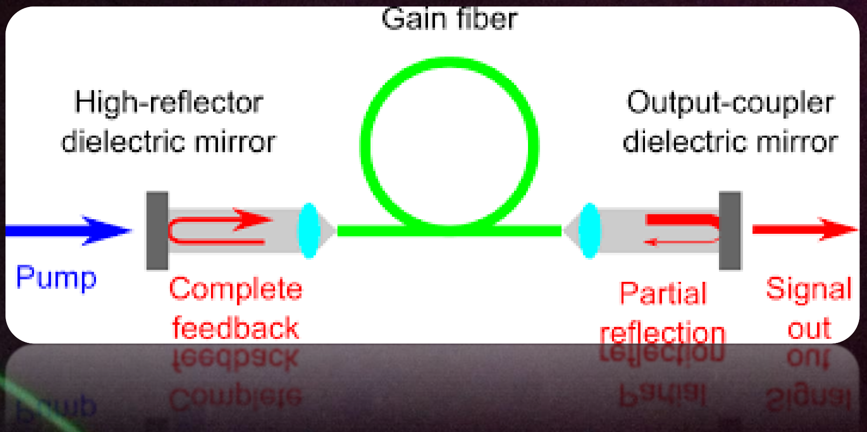
High Power Scaling: Heat is such a nuisance!

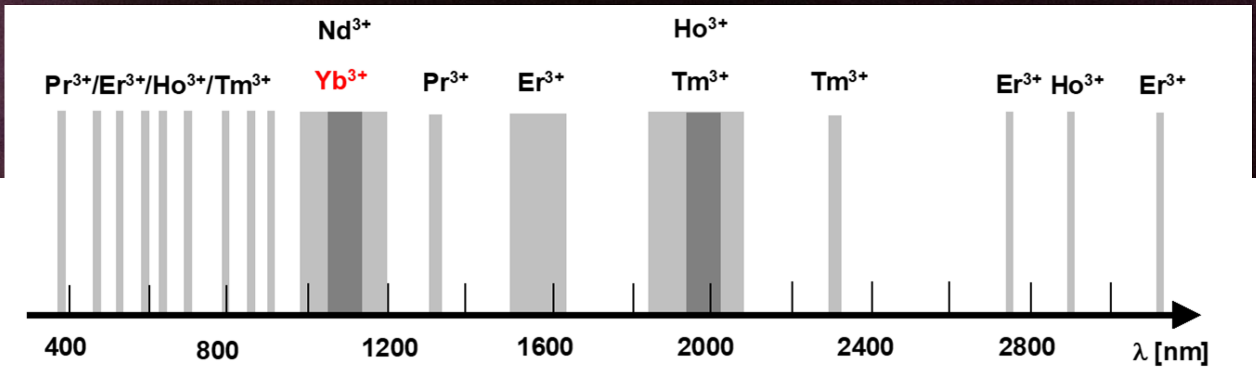
Increase surface-to-volume ratio (fibers, disks)



Fiber Lasers







first demonstration of a fiber laser: in the early sixties !

E. Snitzer, "Neodymium glass laser," Proc. of the Third International conference on Solid Lasers, Paris, page 999 (1963).
C.J. Koester and E.Snitzer, "Amplification in a fiber laser," Appl. Opt. 3, 10, 1182 (1964).

Fiber Lasers

Single-Mode Fiber

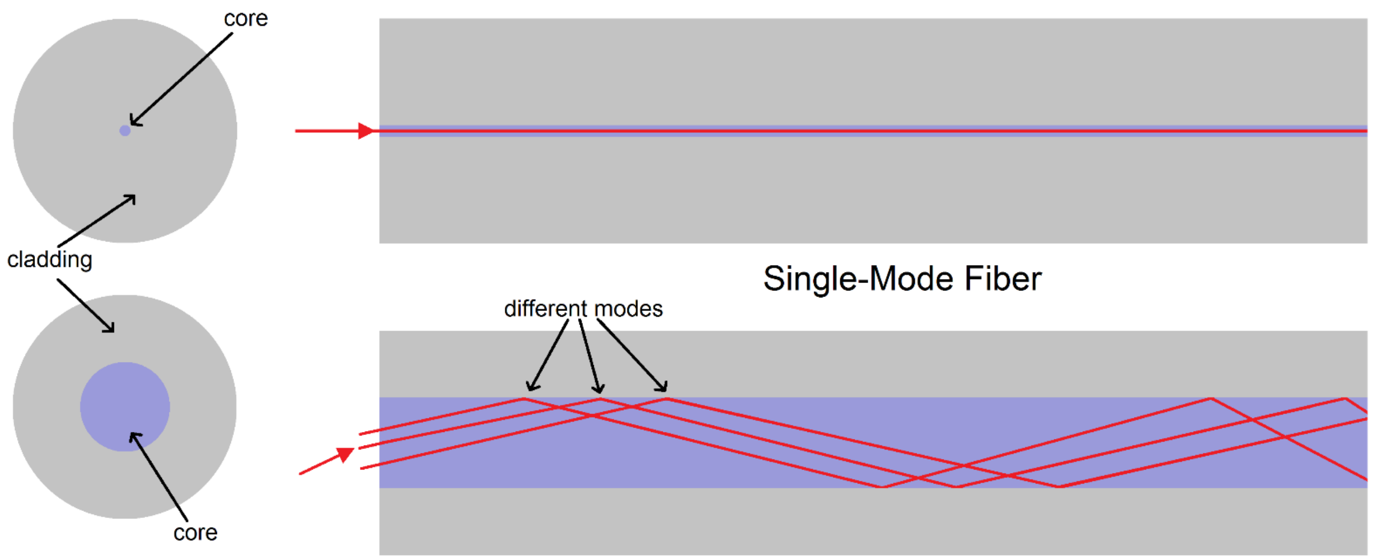
6 µm core / 125 µm cladding

- \+ High Beam Quality
- \- Lower Power Pumping
- \- Expensive Pumping

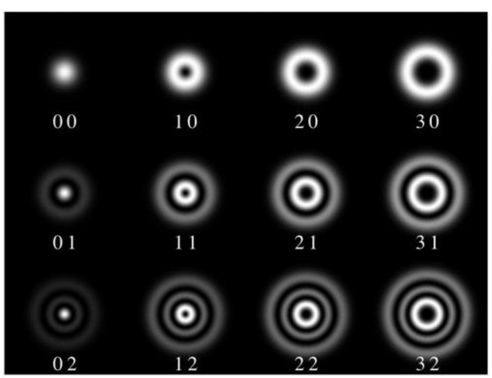
Multimode Fiber

50 µm core / 125 µm cladding

- \+ Higher Power Pumping
- \+ Inexpensive Pumping
- \- Poor Beam Quality



Multimode Fiber

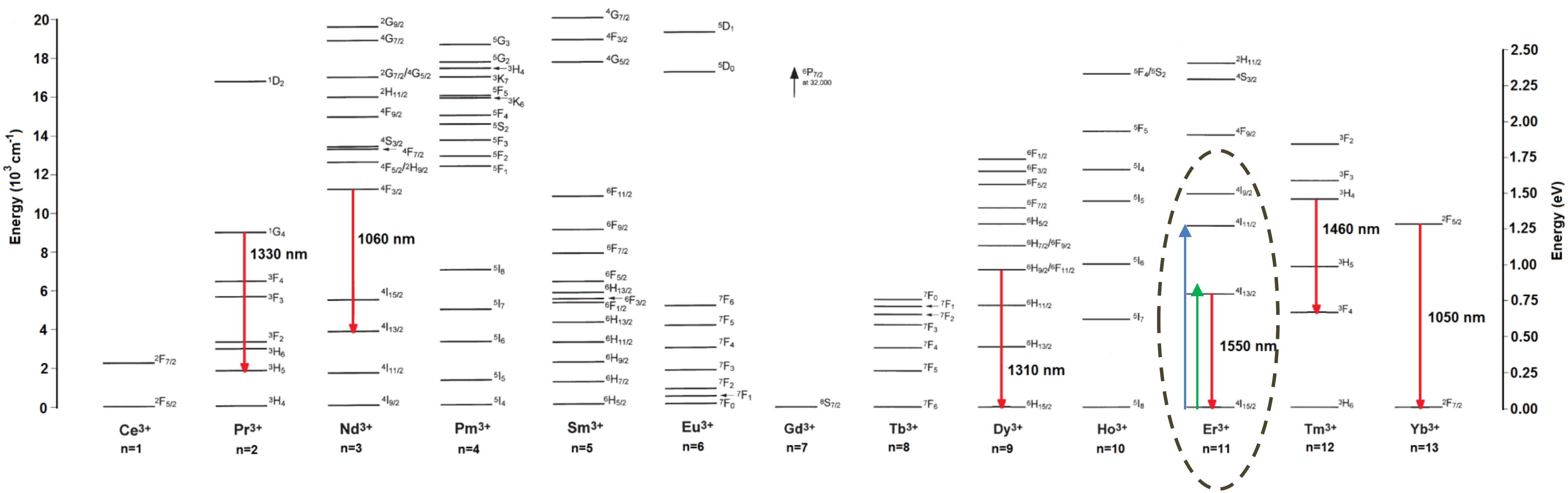


Optical Fiber Modes

Graphics: courtesy of Colin Diehl & Jered Richter

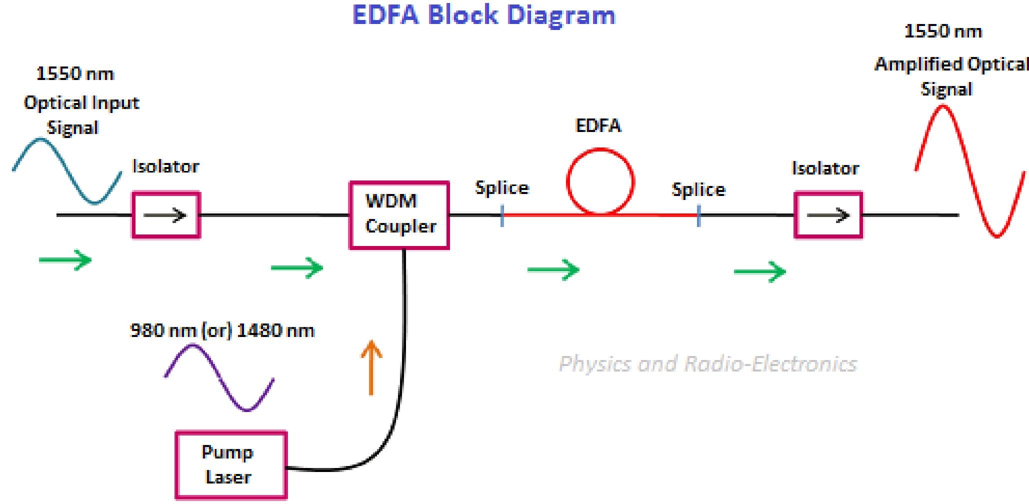
Example: Erbium-Doped fiber Lasers

The wavelength of about 1550 nm is particularly interesting for applications in telecommunication.

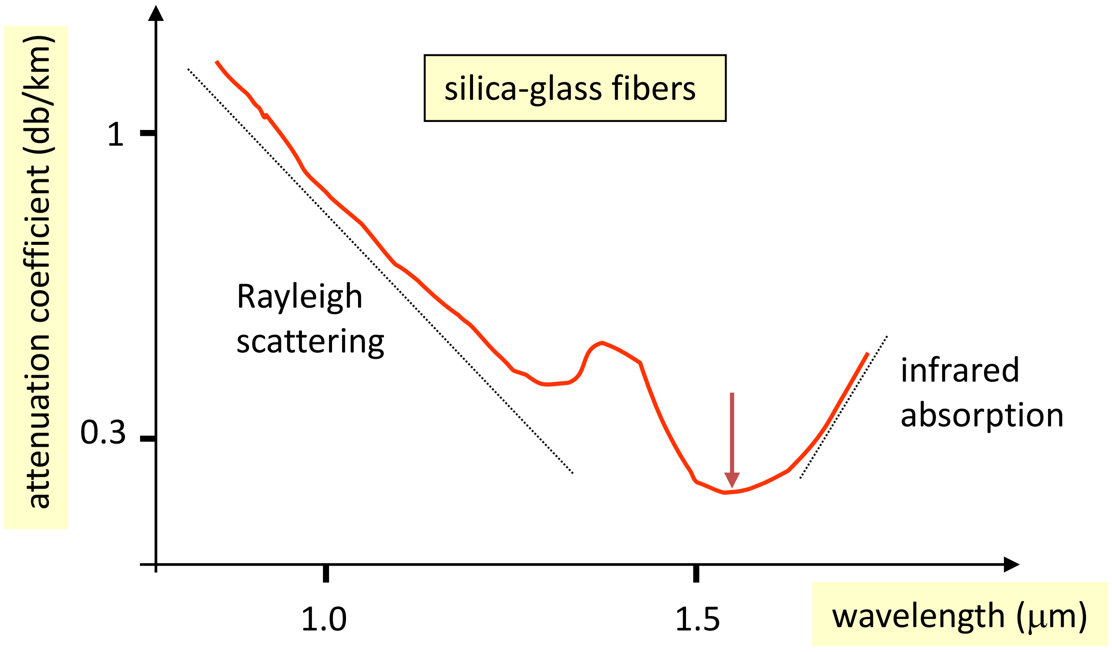


EDFA: Erbium Doped Fiber Amplifier

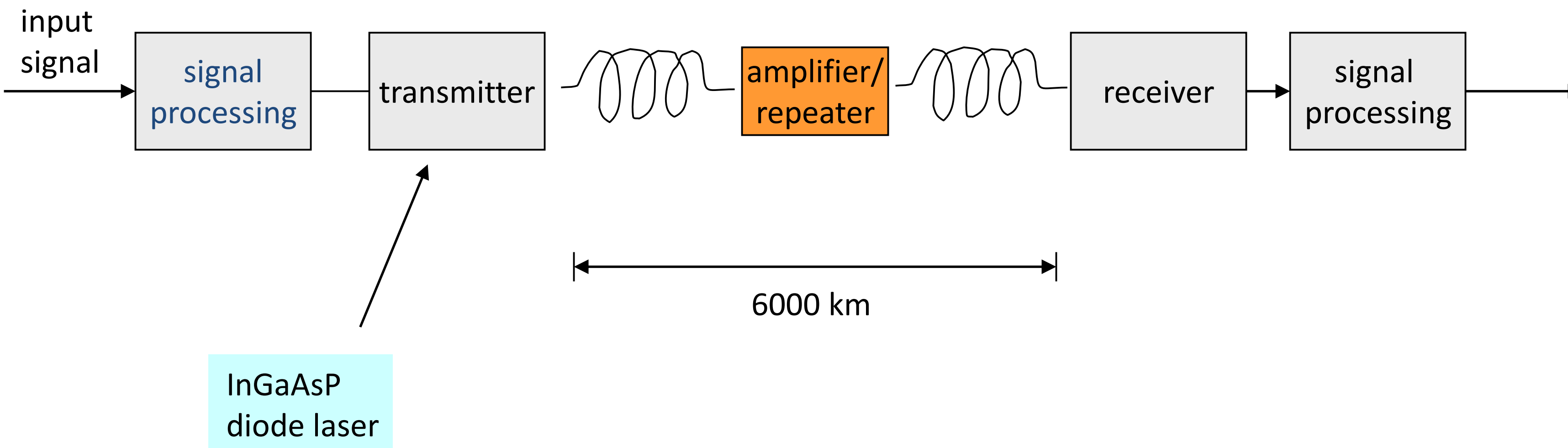
EDFA Block Diagram



Fiber-optic Communications

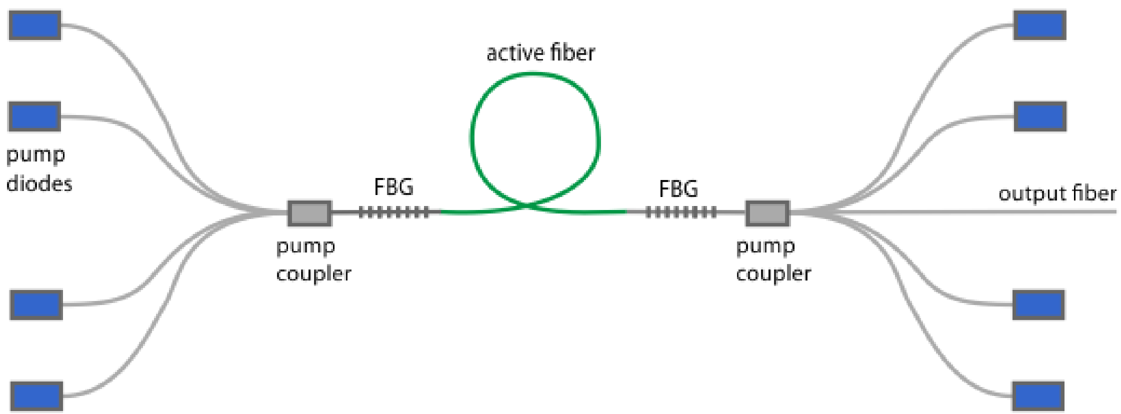


Fiber transmission line

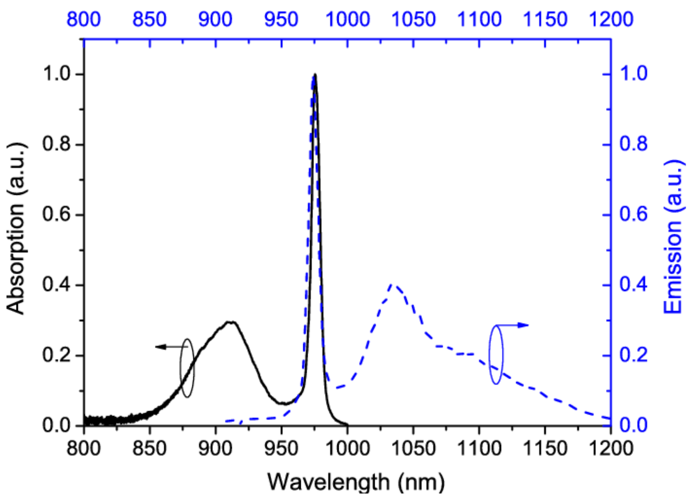


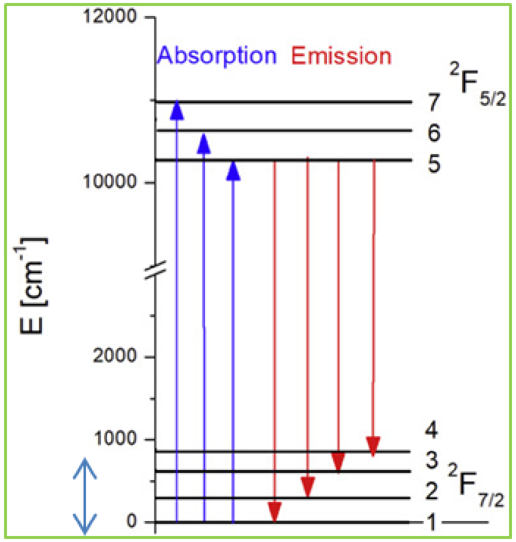
- transatlantic US - UK
- 80000 simultaneous voice channels
- repeaters 100 km apart

High Power Fiber Lasers



Mainly: Yb Silica Fiber Lasers



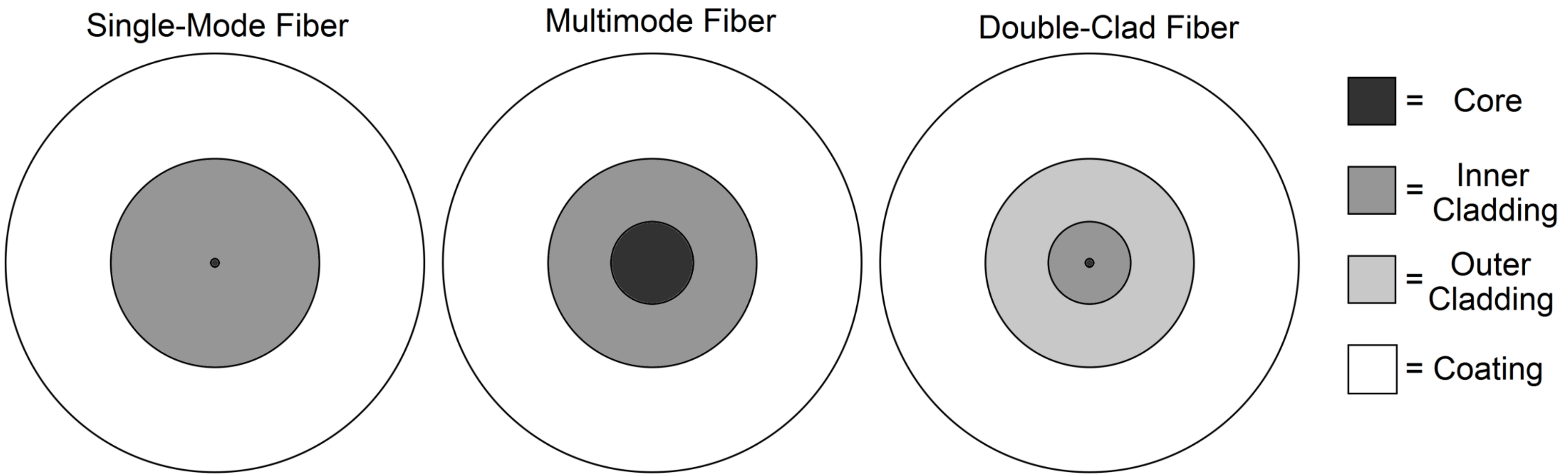


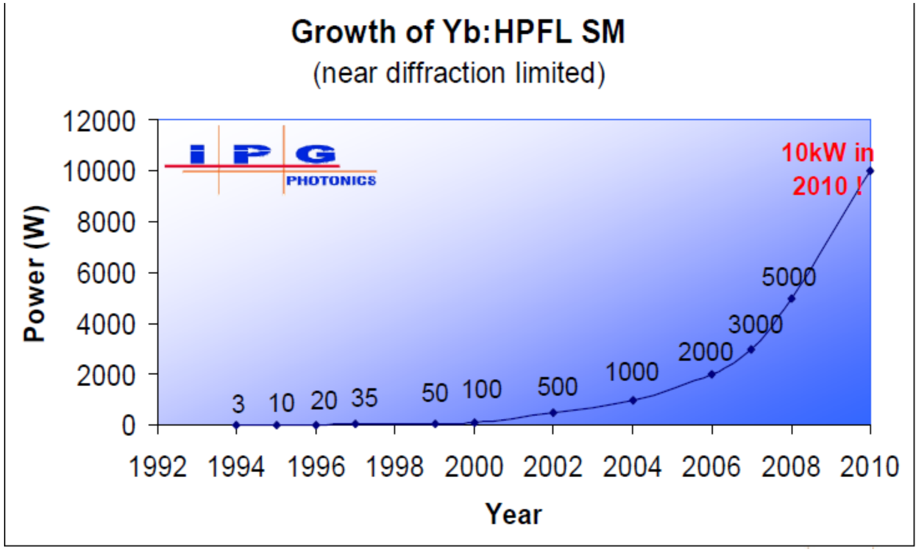
Diode Pumped at 940-980 nm

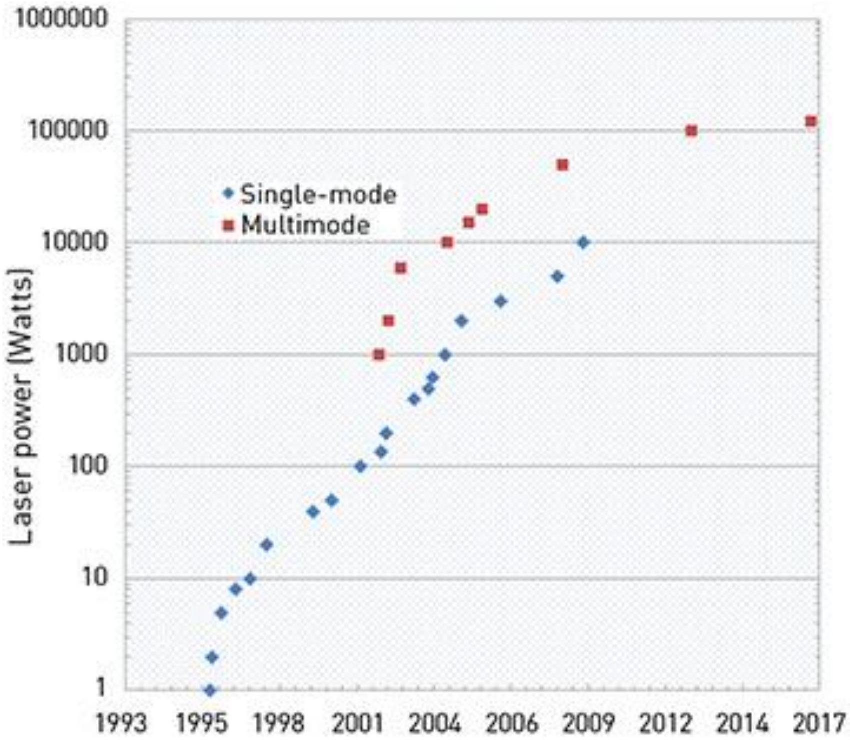
Laser: 1020-1050 nm

High Power Fiber Lasers
Double-Clad Fiber

- Laser light propagates in single-mode core
- Pump light propagates in inner cladding







100 kW (current record)!

IPG Fiber Lasers

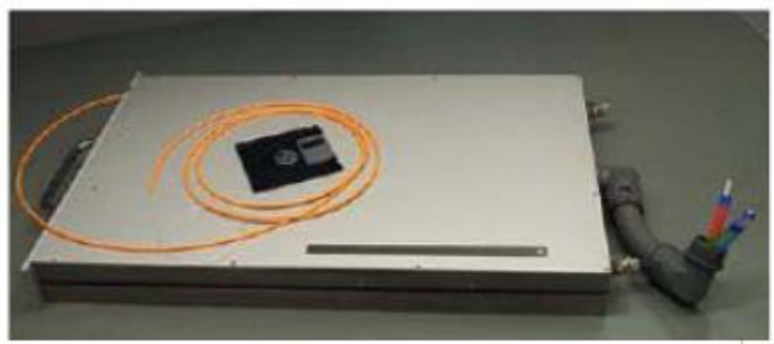
A single module can supply:

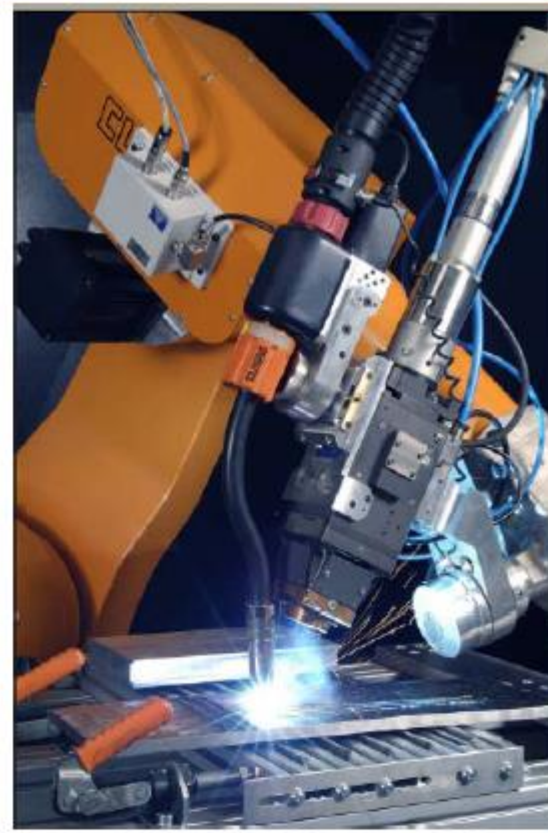
- 250, 400, 800, 1000+ W of laser power
- Wavelength of 1070nm (NIR)
- One 7 or 15 um fiber core
- 0.34-0.41mm*mrad beam divergence

T x H x D = 60 x 33 x 4.7 cm

Efficiency (DC) > 35%

Building blocks (modules) for HPFLs

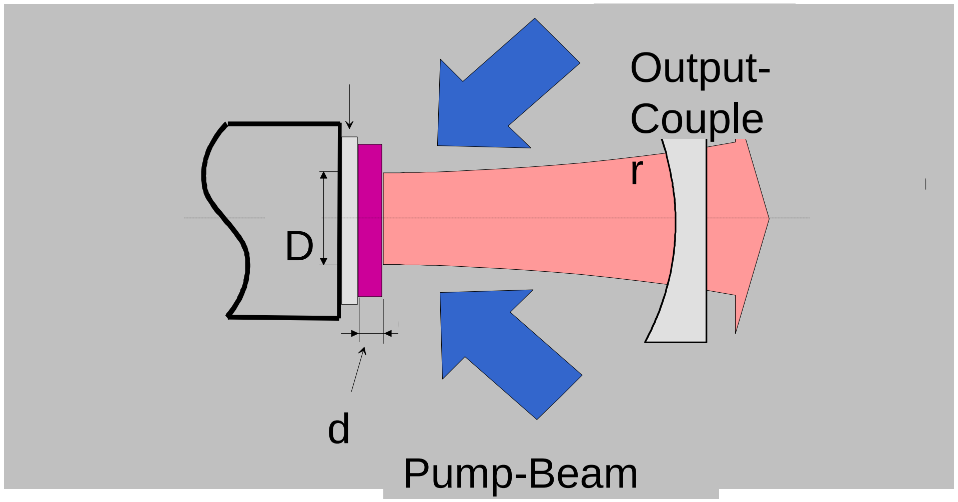




ALAW 2009

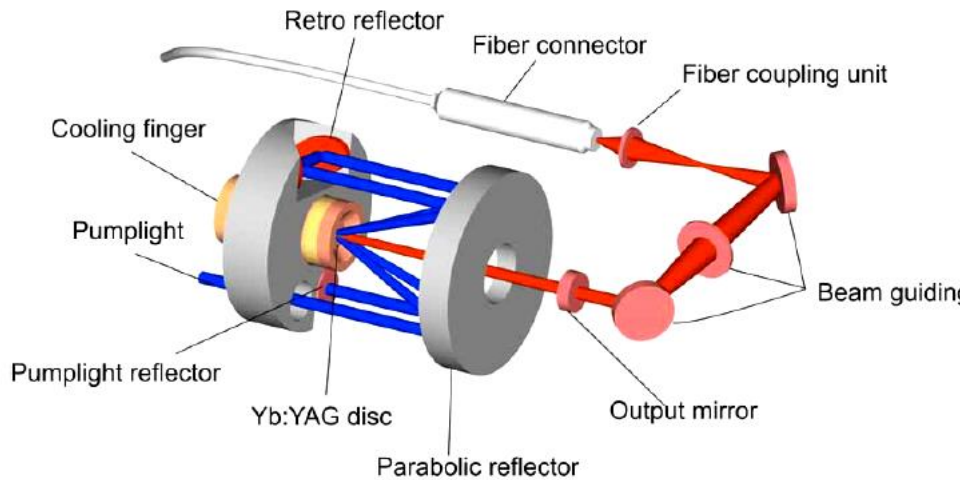
Thin Disk Lasers

Yb:YAG



>10 kW CW

Requires multipass pumping



This principle does show 8 passages through the disc, in actual fact more are performed.

Chemical Lasers

- population inversion is produced by a chemical reaction

$$A + BC \longrightarrow AB + C^*$$

- electrical power supply is not needed
- airborne lasers
- first chemical laser: 1964

chemical reaction:

- exothermic
- generation rate must be large enough to overcome spontaneous emission and collisional relaxation

Examples:

reaction	active medium	wavelength
$F + D_2 \rightarrow DF^* + D$	DF	3.5 - 4.1 μm
$Cl + HI \rightarrow HCl^* + I$	HCl	3.5 - 4.1 μm
$H + Br_2 \rightarrow HBr^* + Br$	HBr	4.0 - 4.7 μm
$F + H_2 \rightarrow HF^* + H$	HF	3.5 - 4.1 μm
$I + O_2^* \rightarrow I^* + O_2$	I	1.31 μm

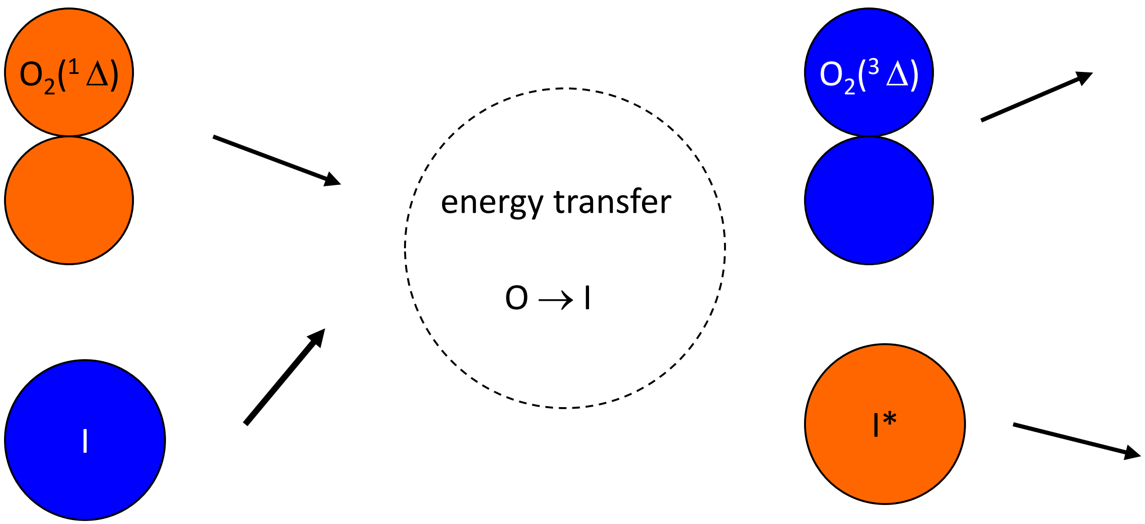
molecules in an excited vibrational state

atoms in an excited electronic state

The chemical oxygen-iodine laser (COIL): MW CW Power !!

Singlet oxygen (dioxidene) has a >40 min lifetime.

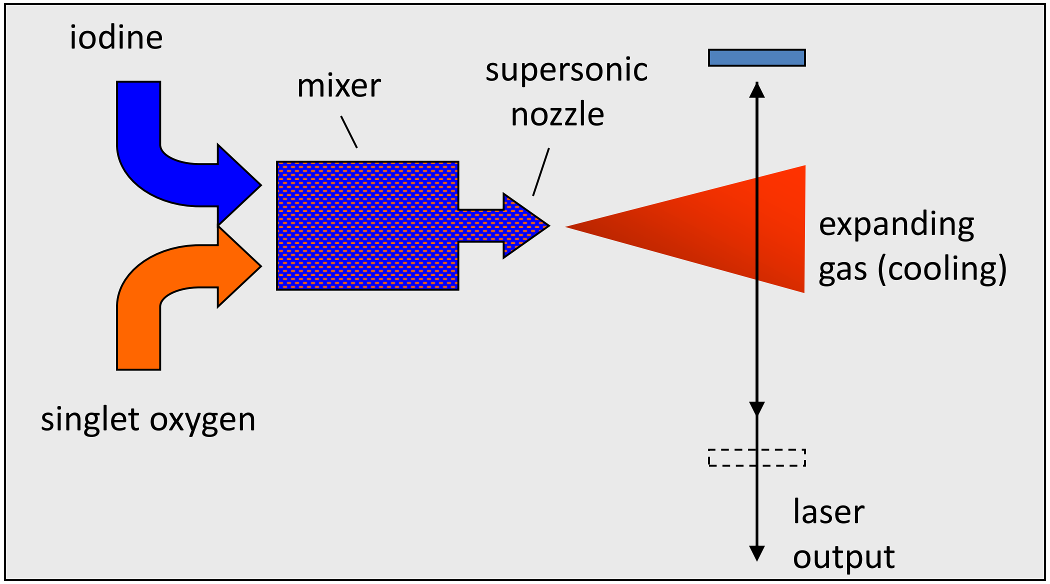
chemical reaction: $O_2(^1\Delta) + I \leftrightarrow O_2(^3\Sigma) + I^*$



steps:

1. generation of singlet oxygen $Cl_2 + H_2O_2 + 2NaOH \rightarrow O_2(^1\Delta) + 2H_2O + 2NaCl$
2. production of excited iodine $O_2(^1\Delta) + I \leftrightarrow O_2(^3\Sigma) + I^*$
3. lasing of excited iodine

schematic diagram of a chemical iodine laser

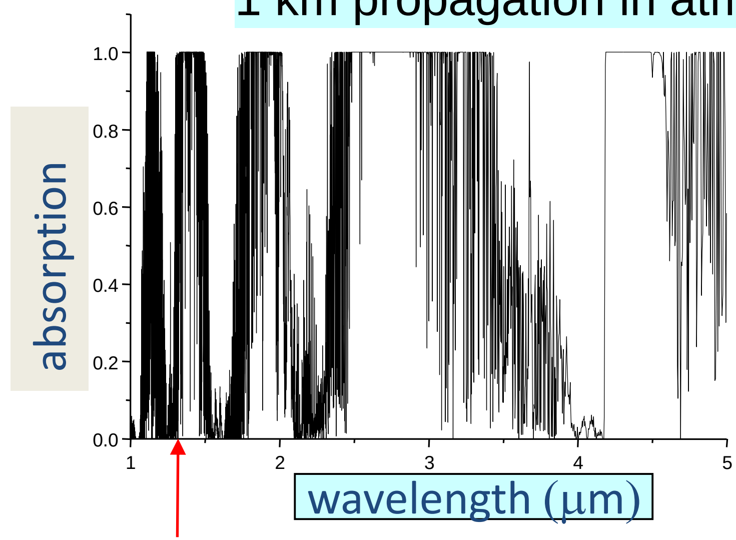


parameters

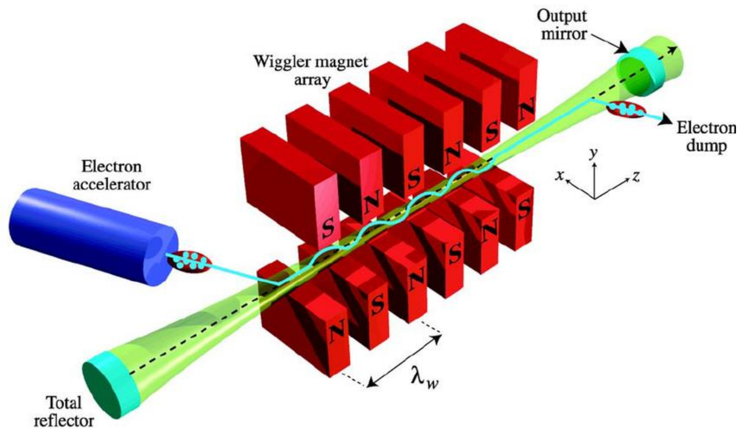
- MW ouput power
- wavelength *1.315* micron
- pulsed and cw

atmospheric absorption

1 km propagation in atmosphere



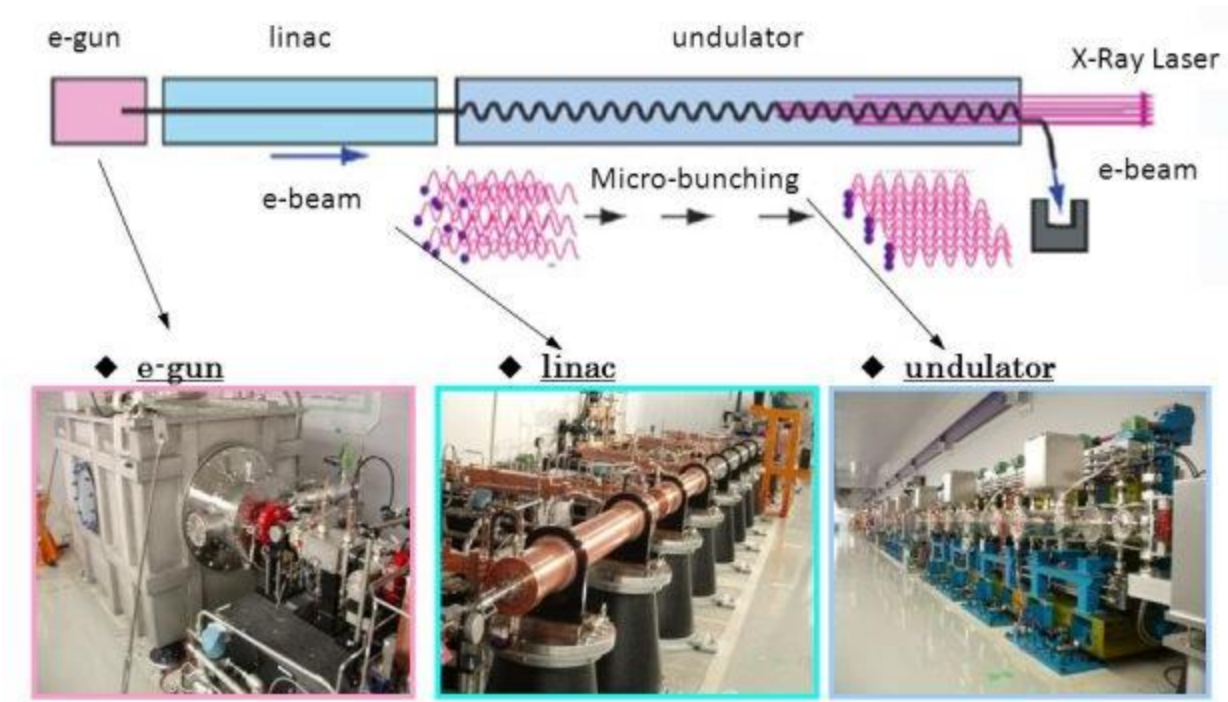
Free Electron Laser (FEL)



wiggler period

$$\lambda_r \approx \frac{\lambda_w}{2\gamma^2}$$

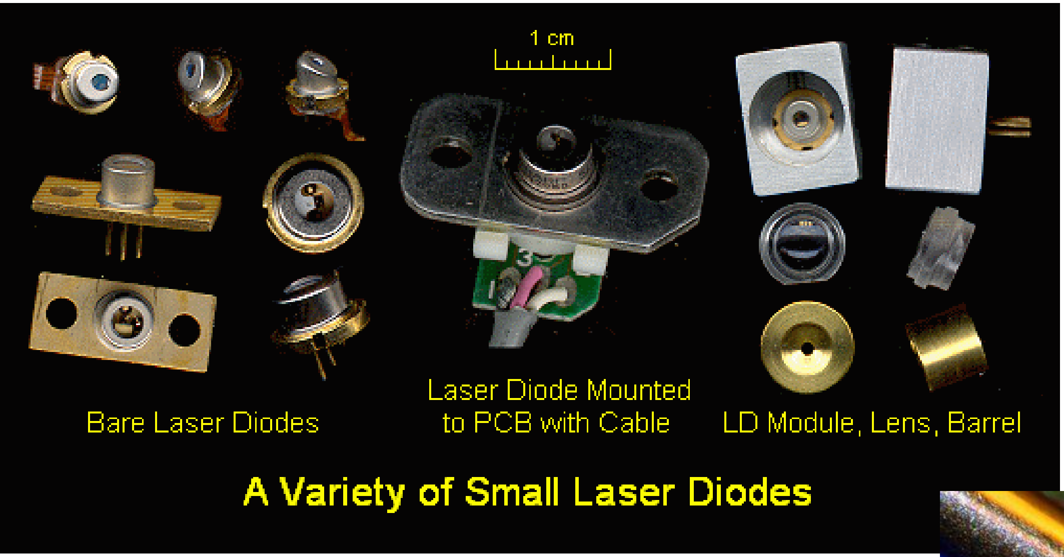
$$\gamma = \frac{1 + K^2/2}{\sqrt{1-\beta^2}} > 10^4$$

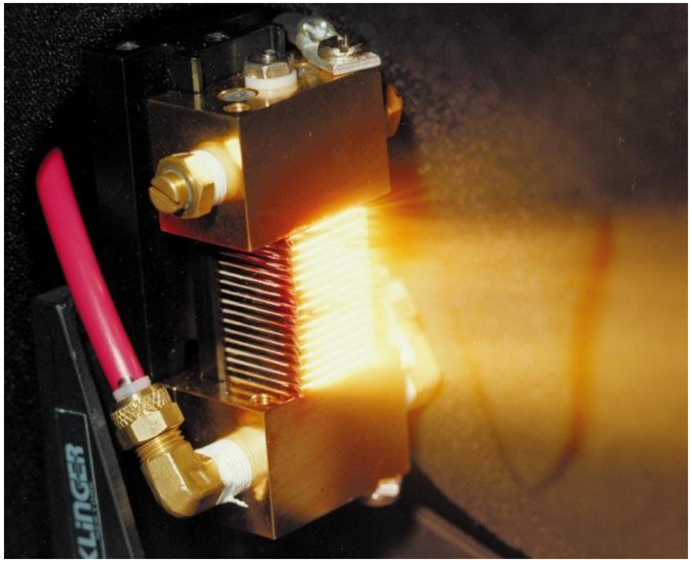


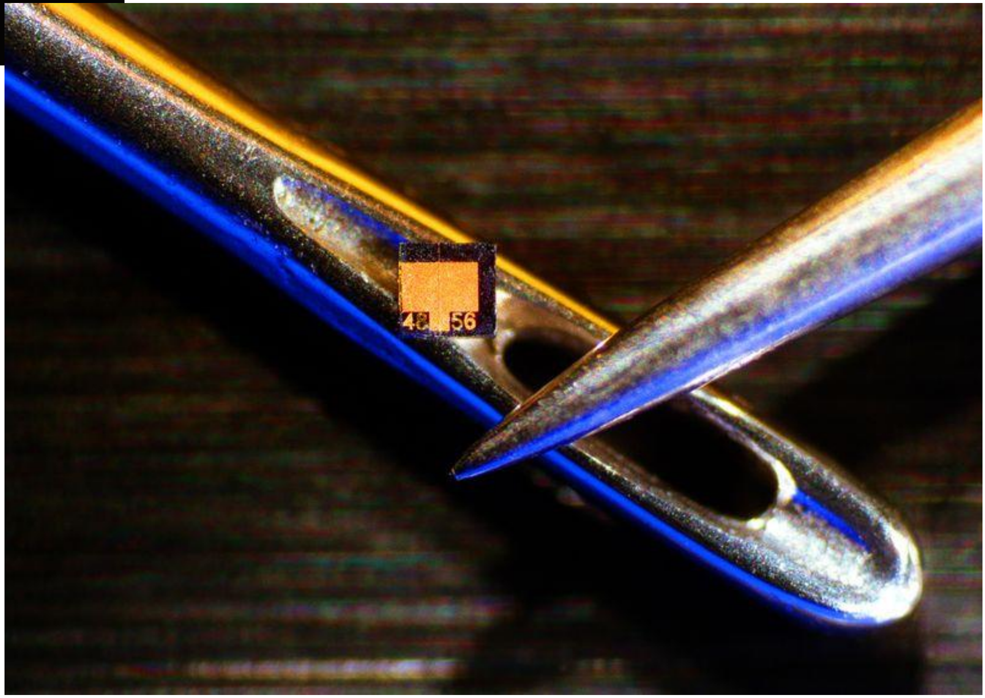
$$K \propto |B|$$

wiggler strength
(often <1)

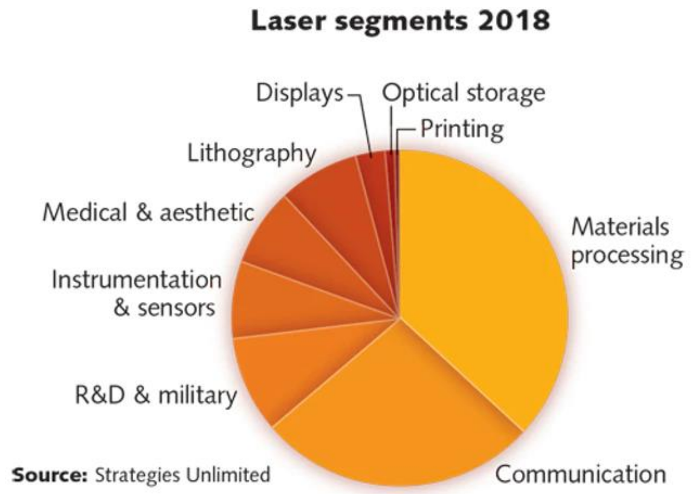
Semiconductor Lasers

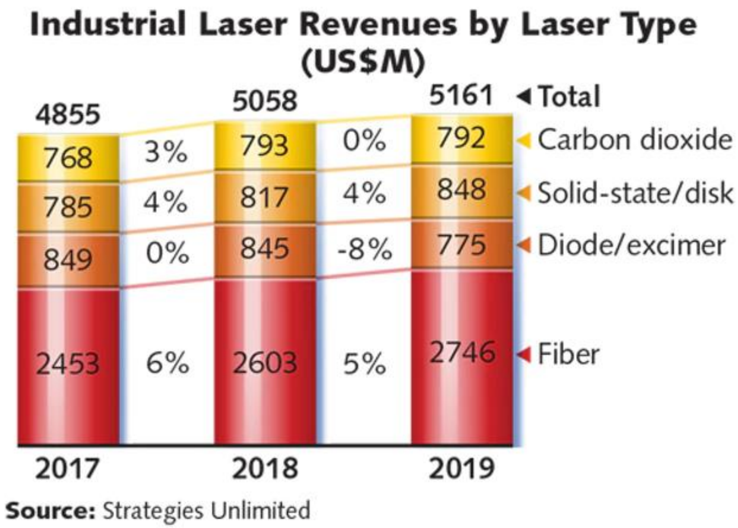


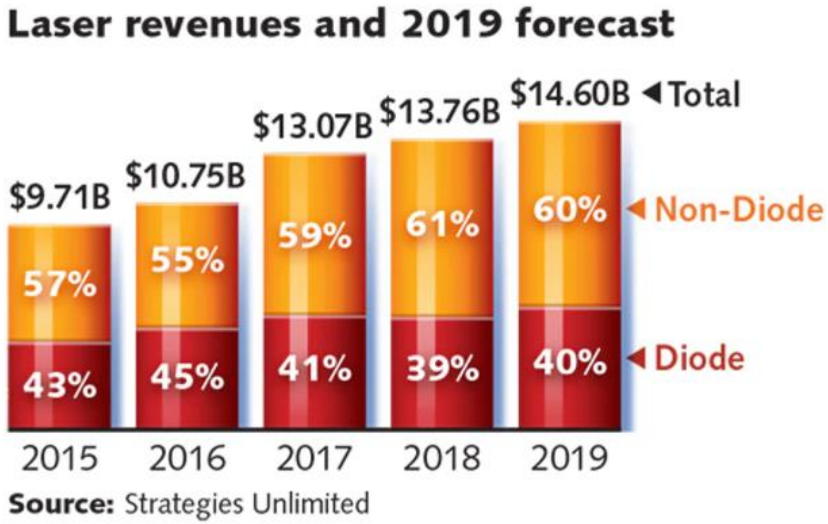




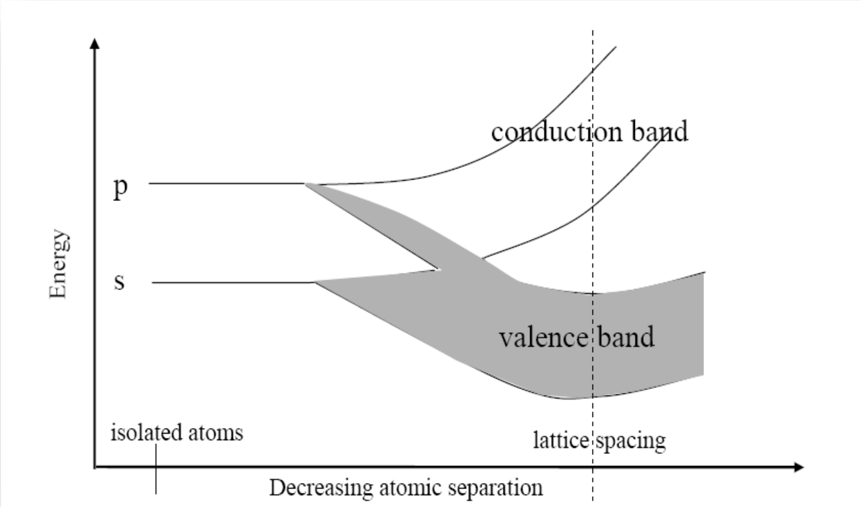
Laser Market and Applications

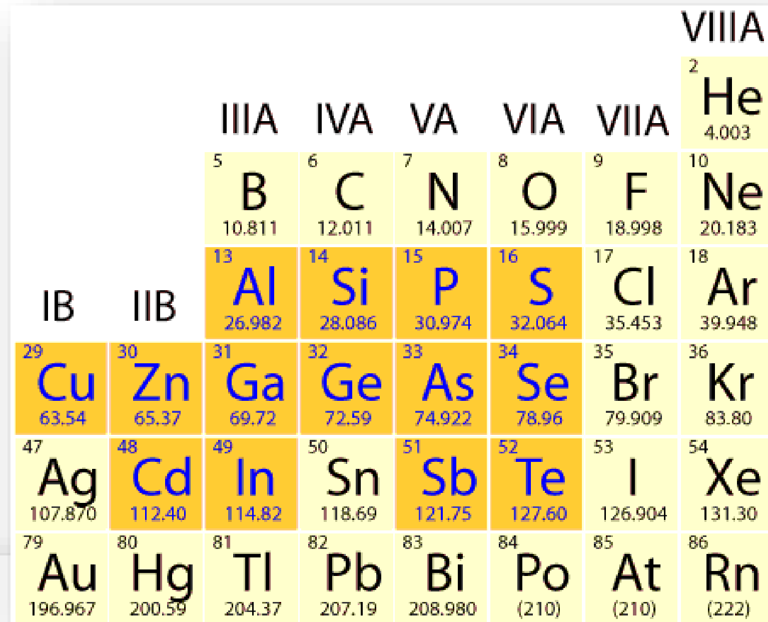


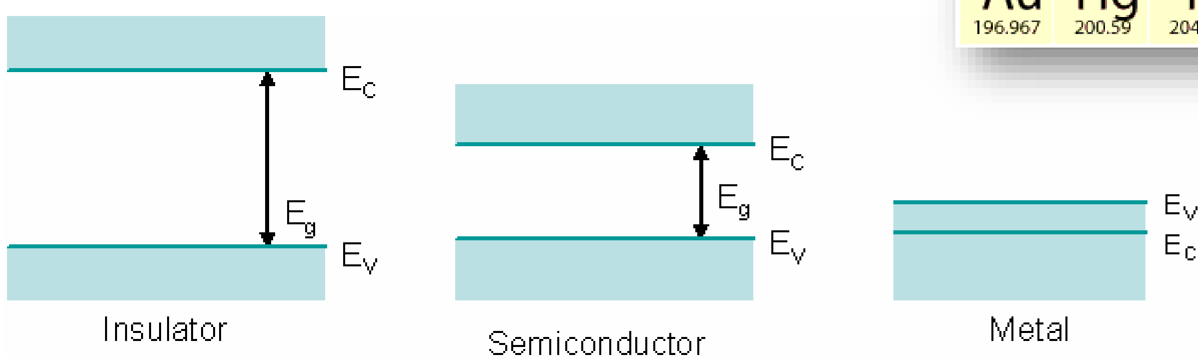




What is a semiconductor?





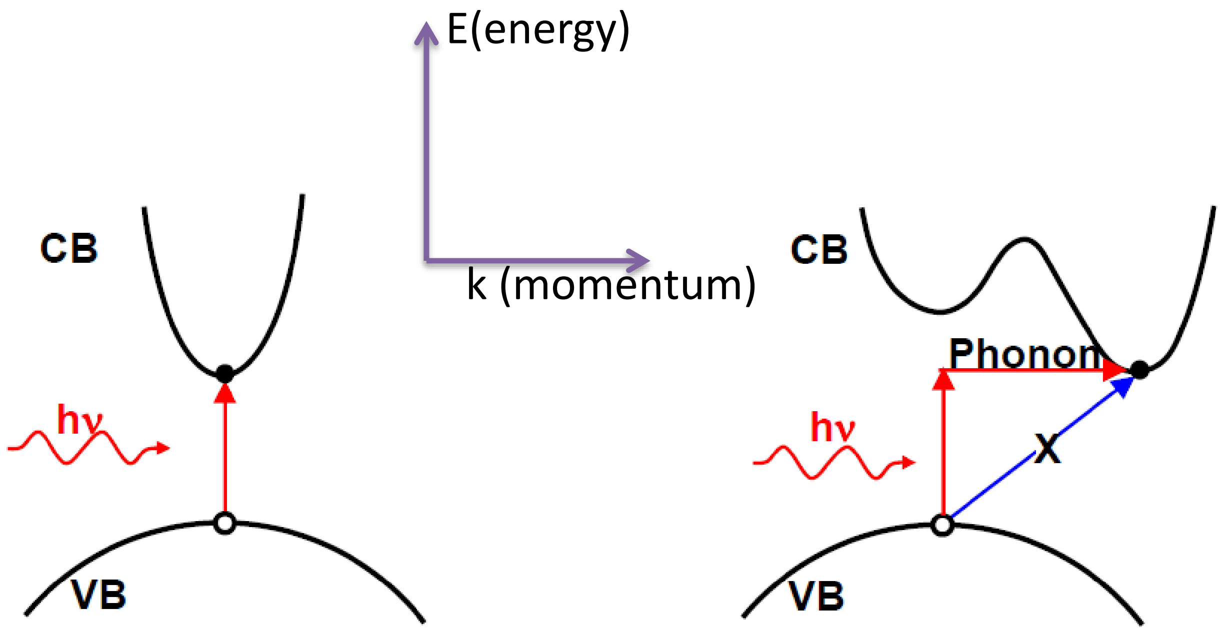


If ↑T → ↑R METAL
→ ↓R SEMICONDUCTOR

Band gap values for some semiconductors →

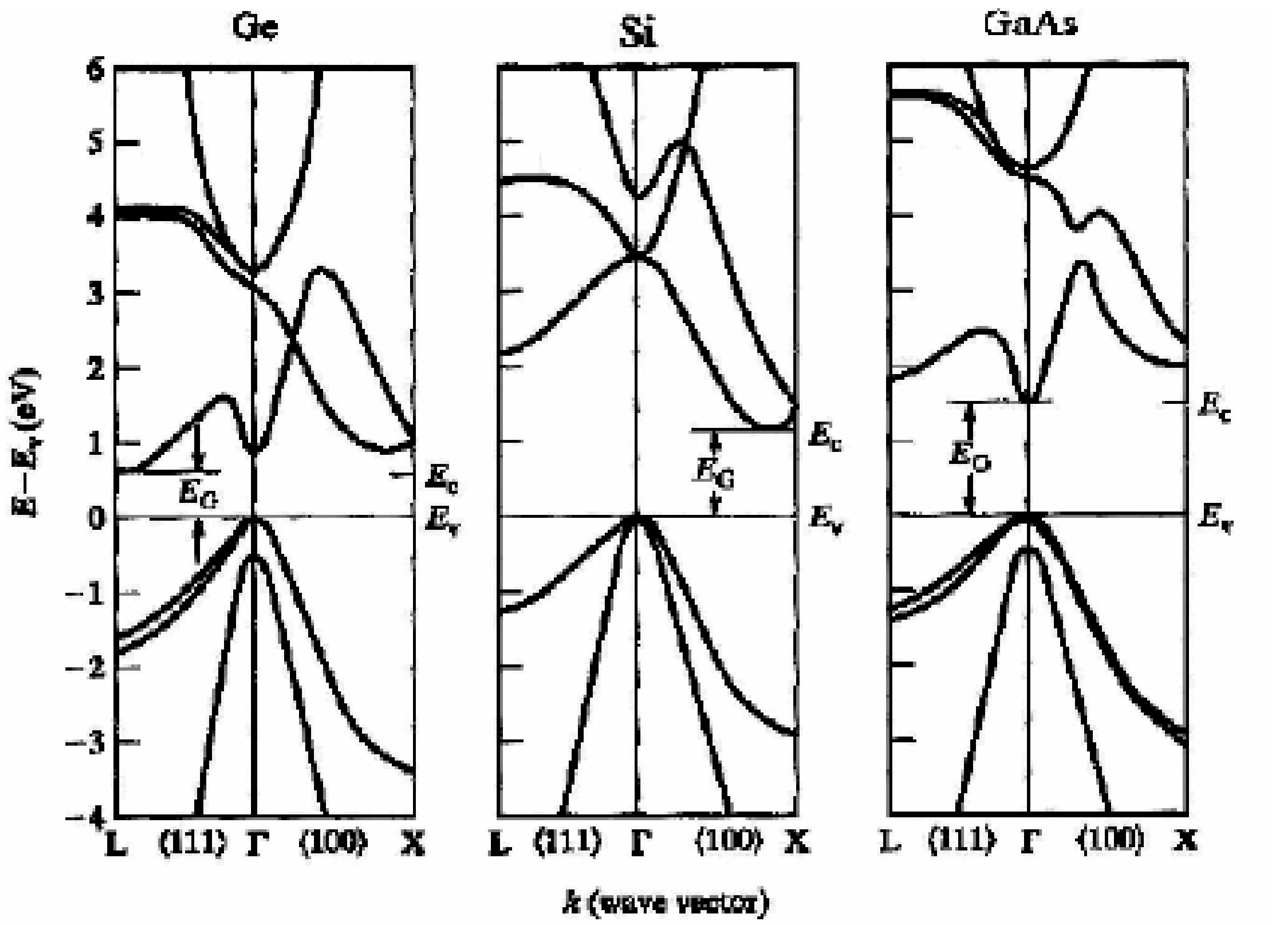
	Ge	Si	GaAs	GaN
E_g (eV)	0,66	1,12	1,42	3,44

Direct-Gap vs. Indirect-Gap



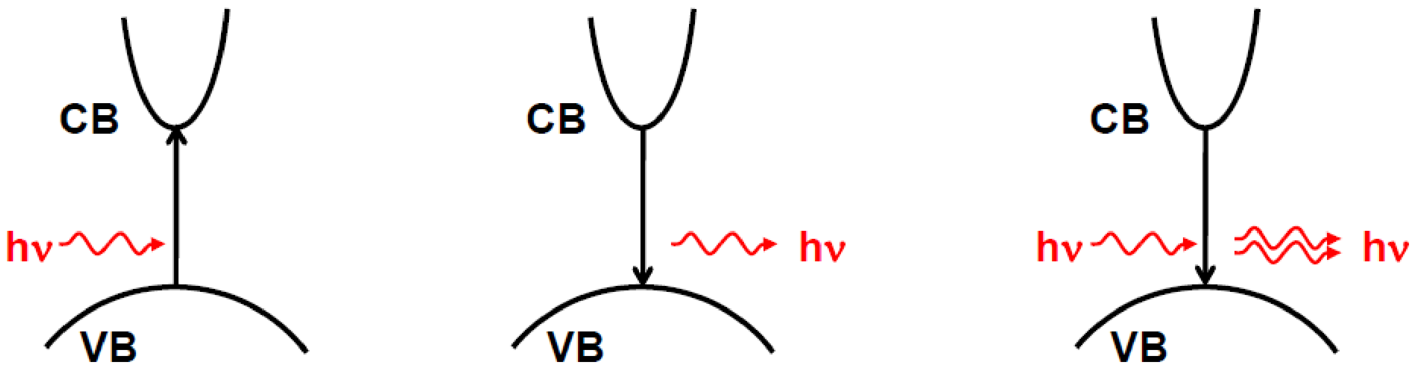
- Direct bandgap materials
  - CB minimum and VB maximum occur at the same k
  - Examples
    - GaAs, InP, InGaAsP
    - $(Al_xGa_{1-x})As$, $x < 0.45$
- Indirect bandgap materials
  - CB minimum and VB maximum occur at different k
  - Example
    - Si, Ge
    - $(Al_xGa_{1-x})As$, $x > 0.45$
  - Not "optically active"

E-k diagrams



Ge
Si
GaAs
E − E_v (eV)
6
5
4
3
2
1
0
−1
−2
−3
−4
E_G
E_c
E_v
E_G
E_c
E_v
E_G
E_c
E_v
L (111) Γ (100) X
L (111) Γ (100) X
L (111) Γ (100) X
k (wave vector)

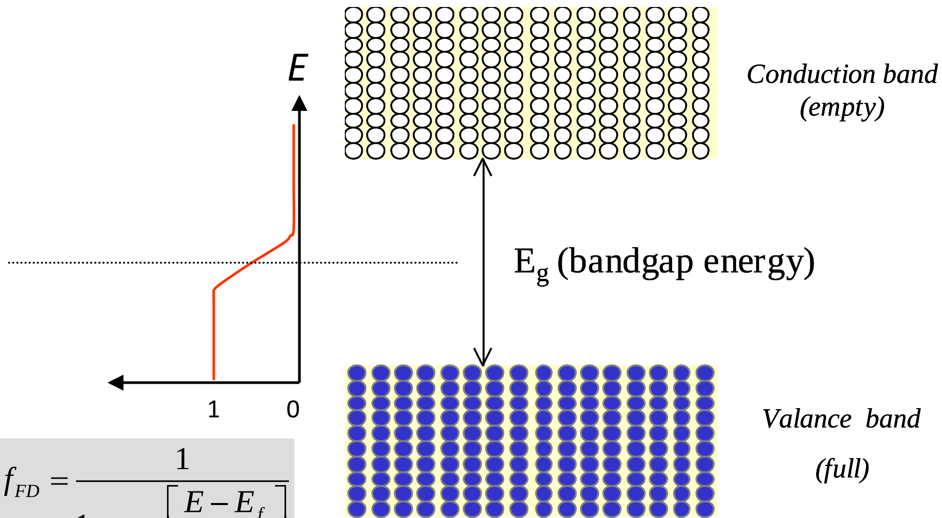
Optical Interactions in a Direct-Gap Semiconductor



Absorption	Spontaneous Emission	Stimulated Emission
↓	↓	↓
Photodetectors; Solar Cells	LED	Optical Amplifiers; Semiconductor Lasers

A Brief Introduction to Semiconductors

Energy Bands

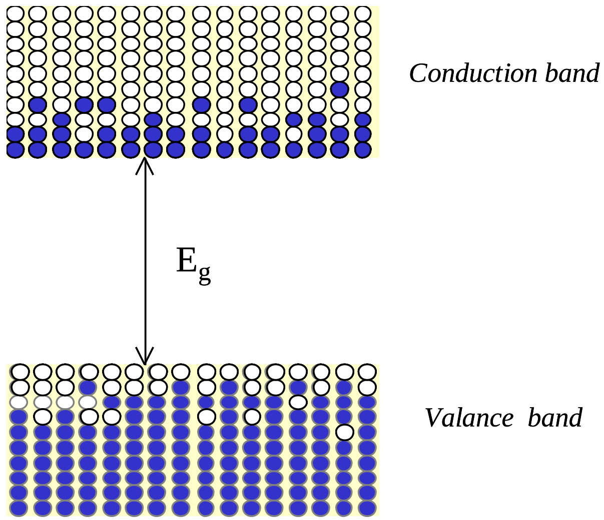


$$f_{FD} = \frac{1}{1 + \exp\left[\frac{E - E_f}{kT}\right]}$$

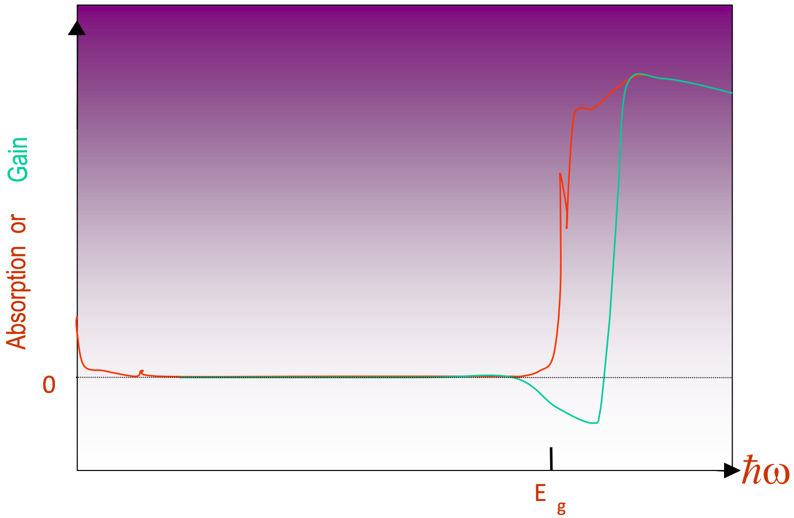
Fermi-Dirac Statistics

Equilibrium

http://britneyspears.ac/lasers.htm !!!???



Nonequilibrium Electron-Hole Injection



Example

GaAs

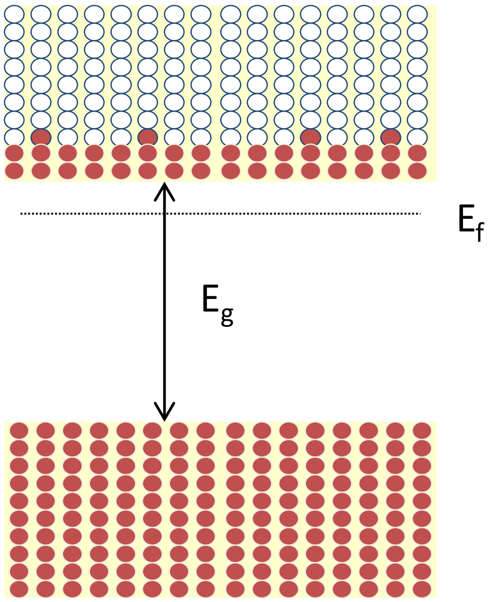
E_g=1.4 eV

(λ_g=850 nm)

p-n junctions

Doping with Impurities

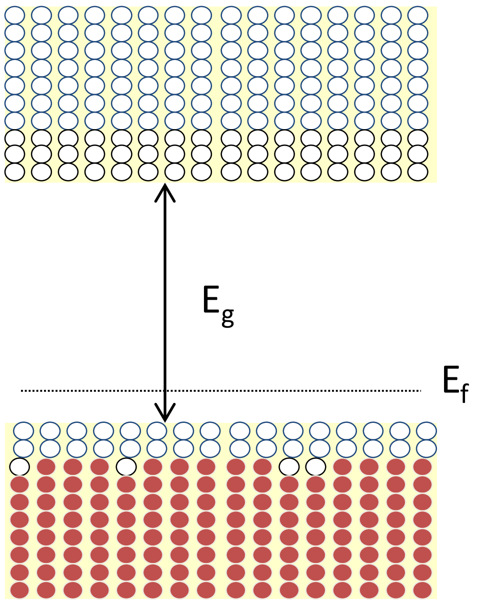
n-type



Examples: GaAs doped with Br

Si doped with P

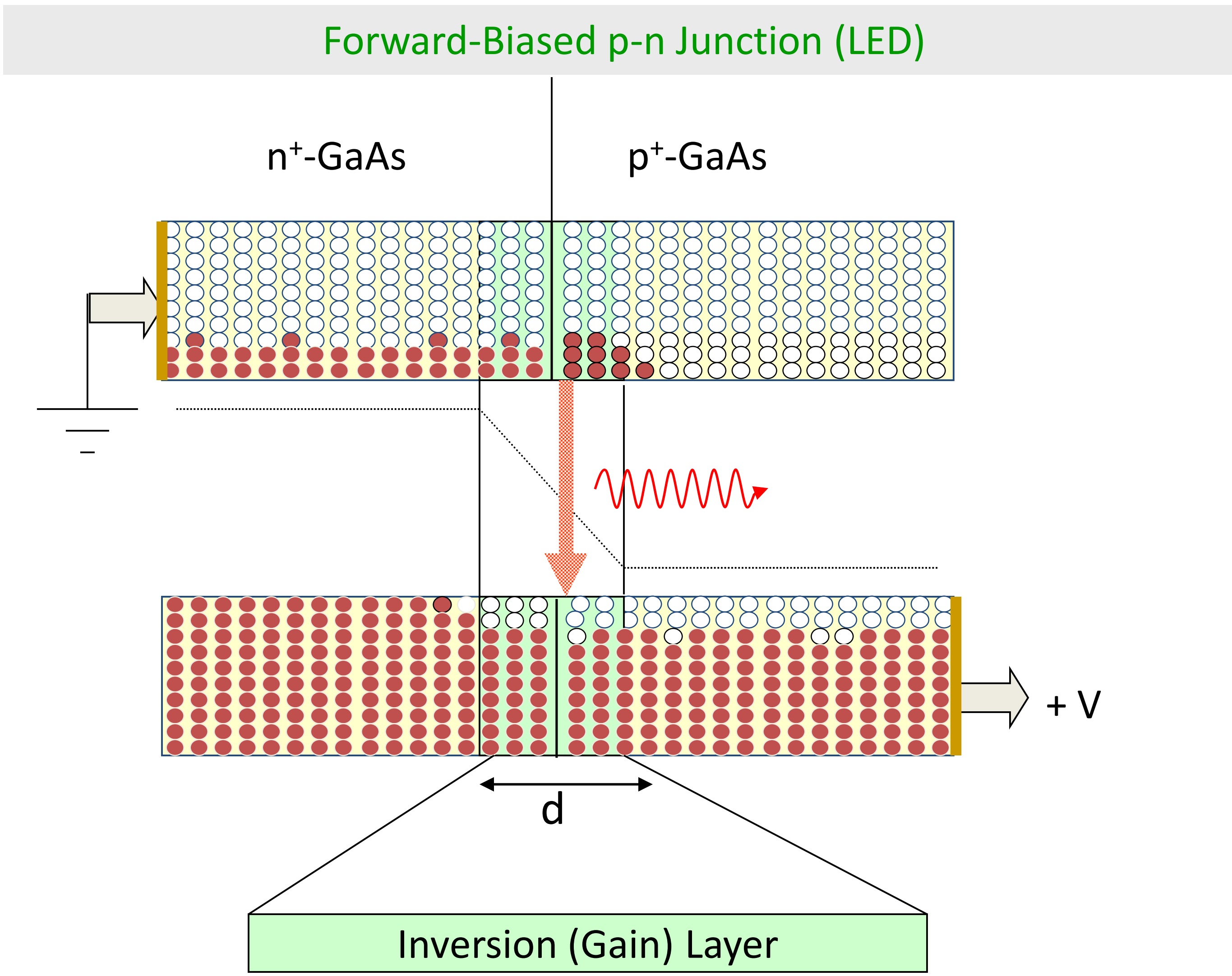
p-type



Examples: GaAs doped with Zn

Si doped with Al

Semiconductor junction lasers

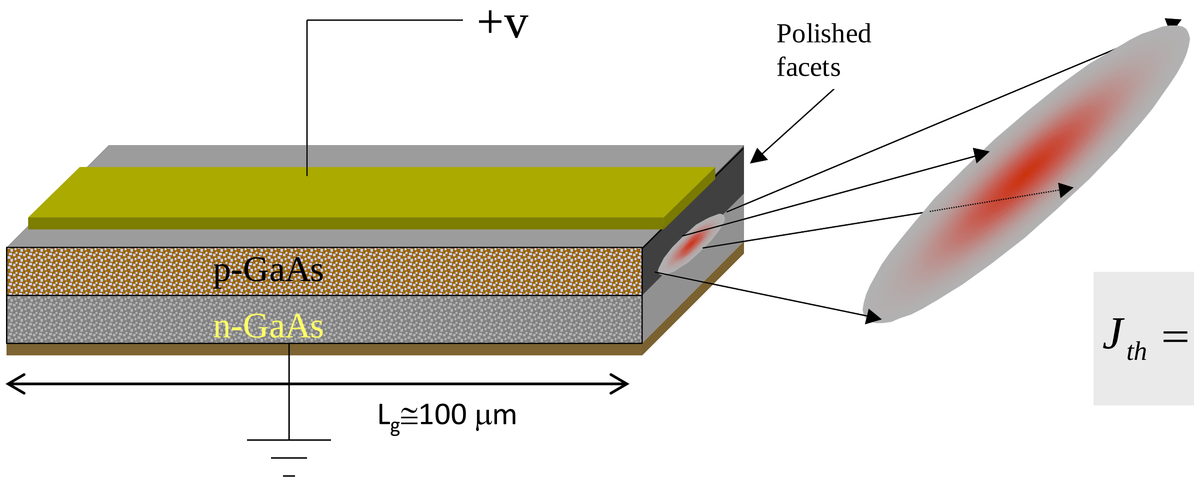


Current Density Threshold

$$J_{th} = \frac{N_{e,h} e d}{\tau_r}$$

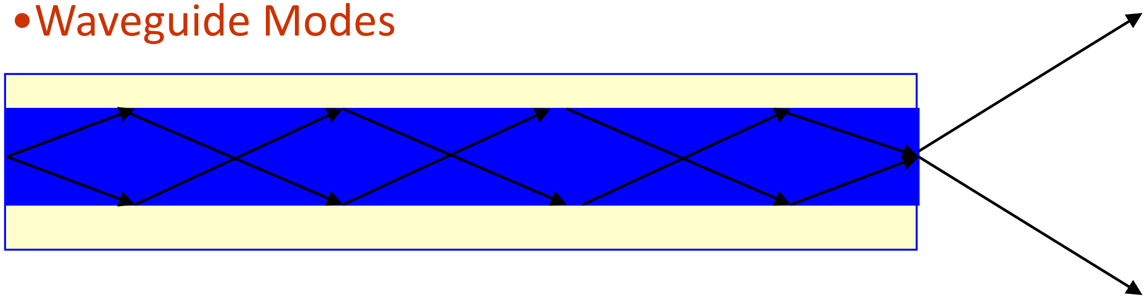
Recombination time

Edge-Emitting Homojunction Laser Diodes



$$J_{th} = \frac{N_{e,h} e d}{\tau_r}$$

•Waveguide Modes

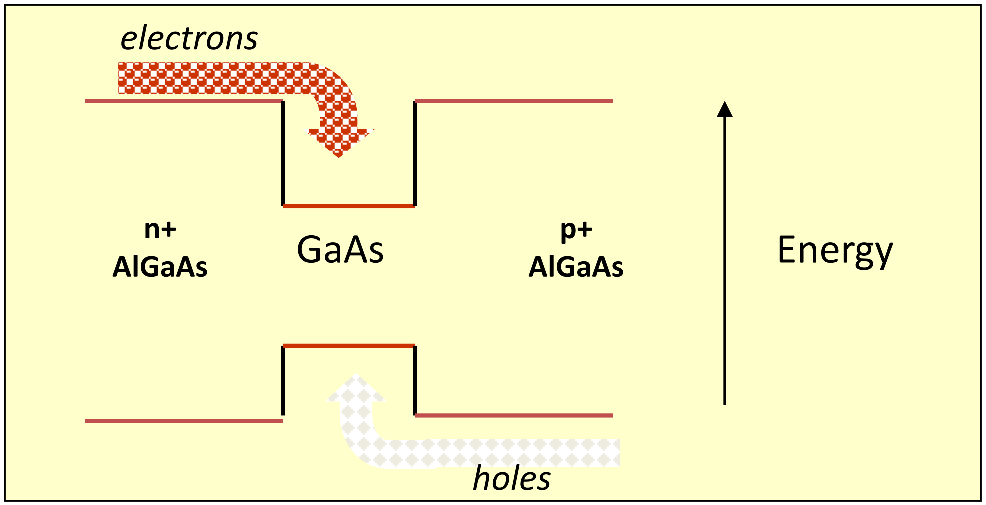


Homojunction Lasers have very high current threshold mainly because.

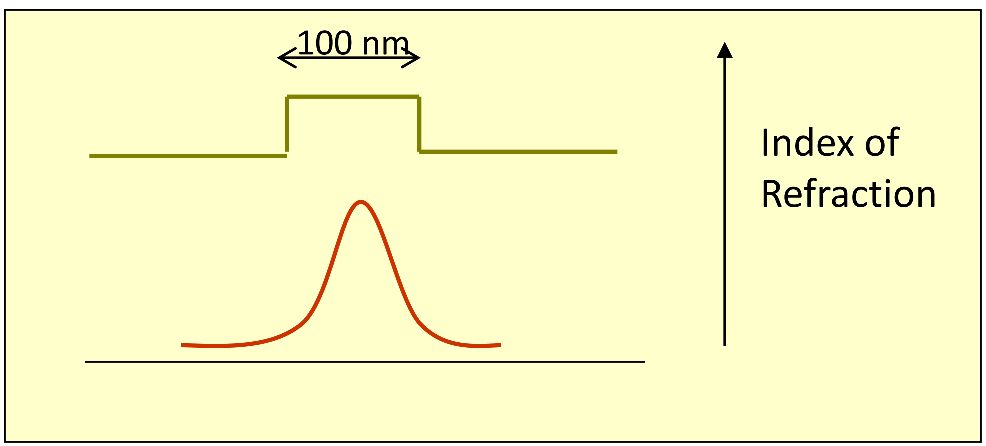
- *Electrons and holes are free to diffuse and therefore dilute the gain (no carrier confinement)*
- *Optical mode has poor overlap with gain (no optical confinement or guiding)*

12.3 Heterojunction Lasers Diodes

A fortunate coincidence: $n \uparrow$ when $E_g \downarrow$

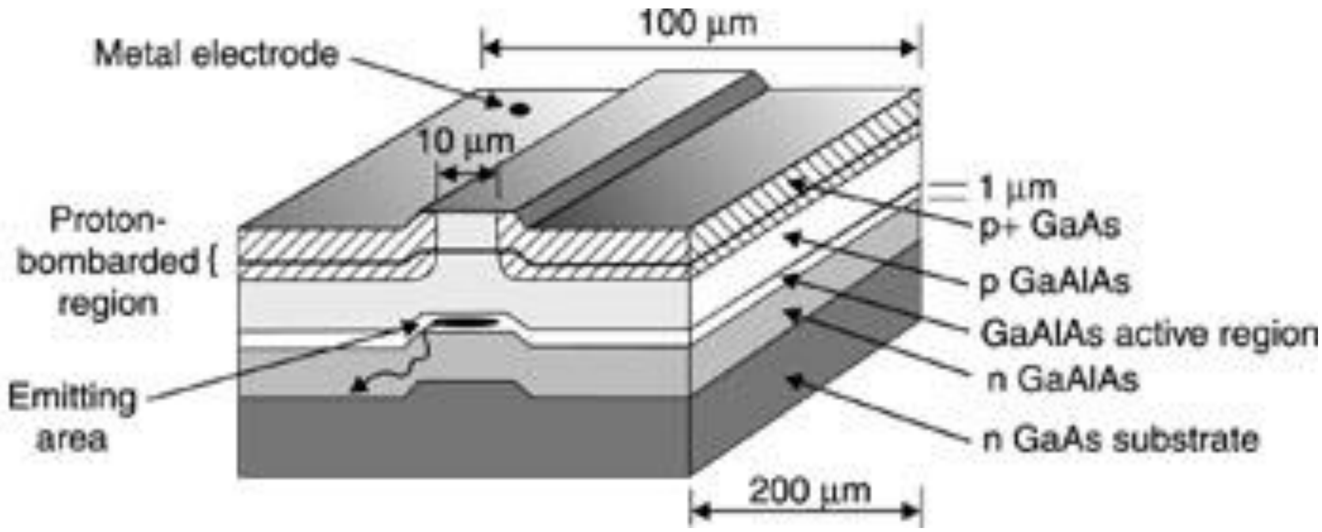


Carrier confinement

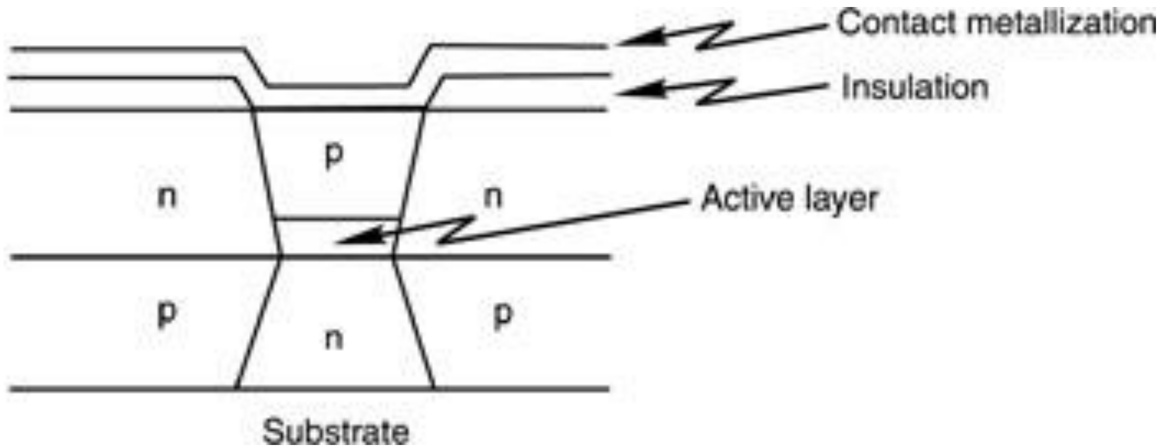


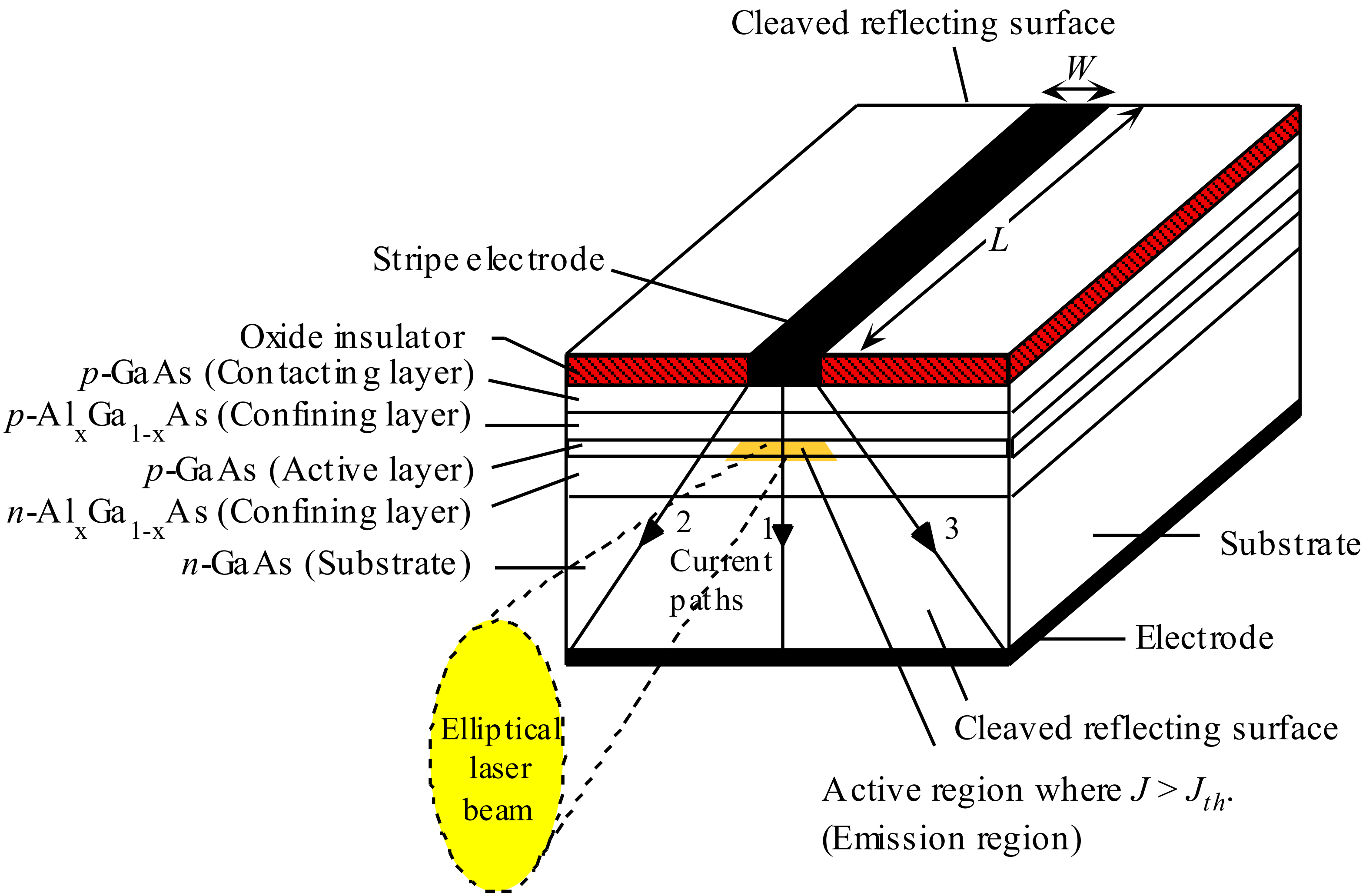
Mode confinement

Edge-Emitting Heterojunction Laser Diodes



Edge-Emitting Buried Heterojunction Laser Diodes

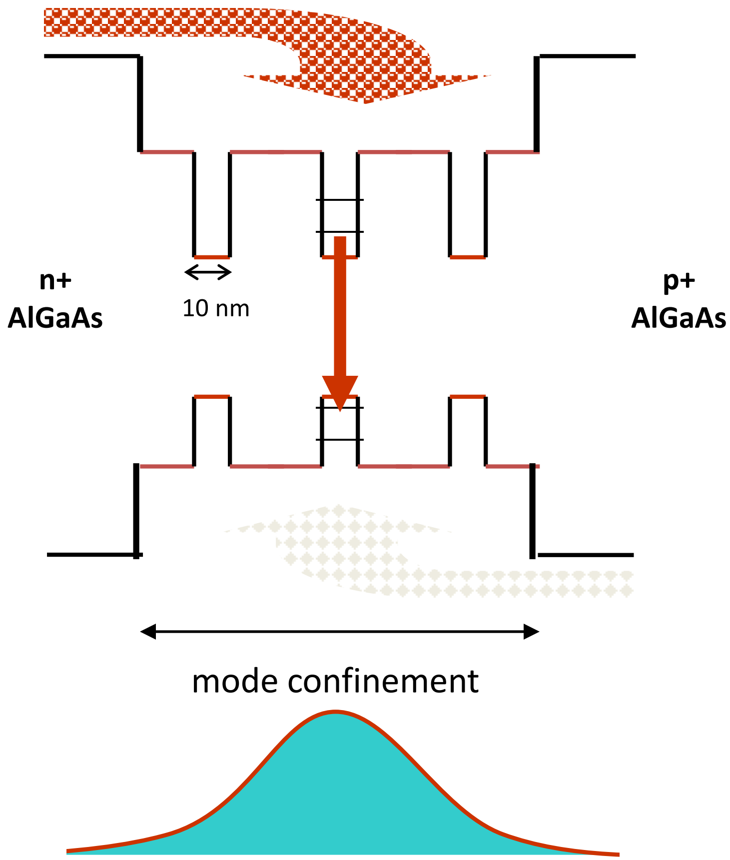


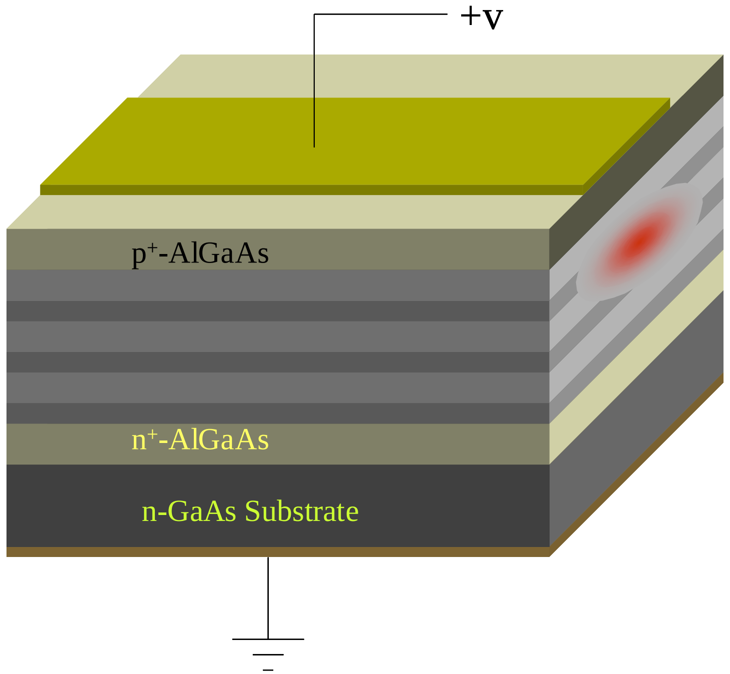


Schematic illustration of the the structure of a double heterojunction stripe contact laser diode

12.4 Quantum Well Lasers

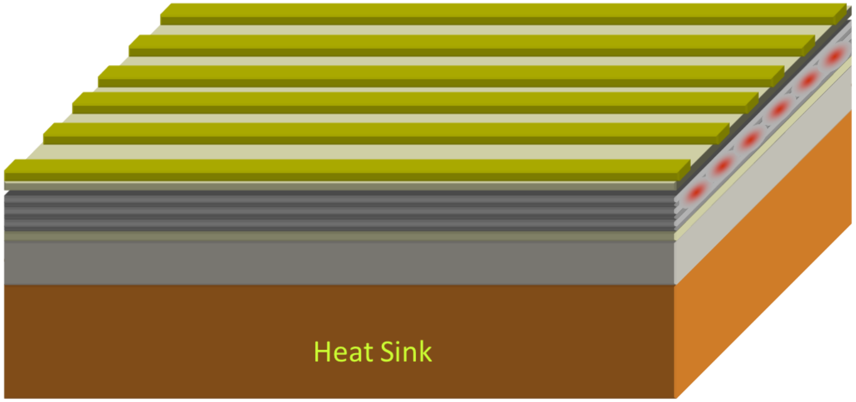
Multiple Quantum Well (MQW) Lasers

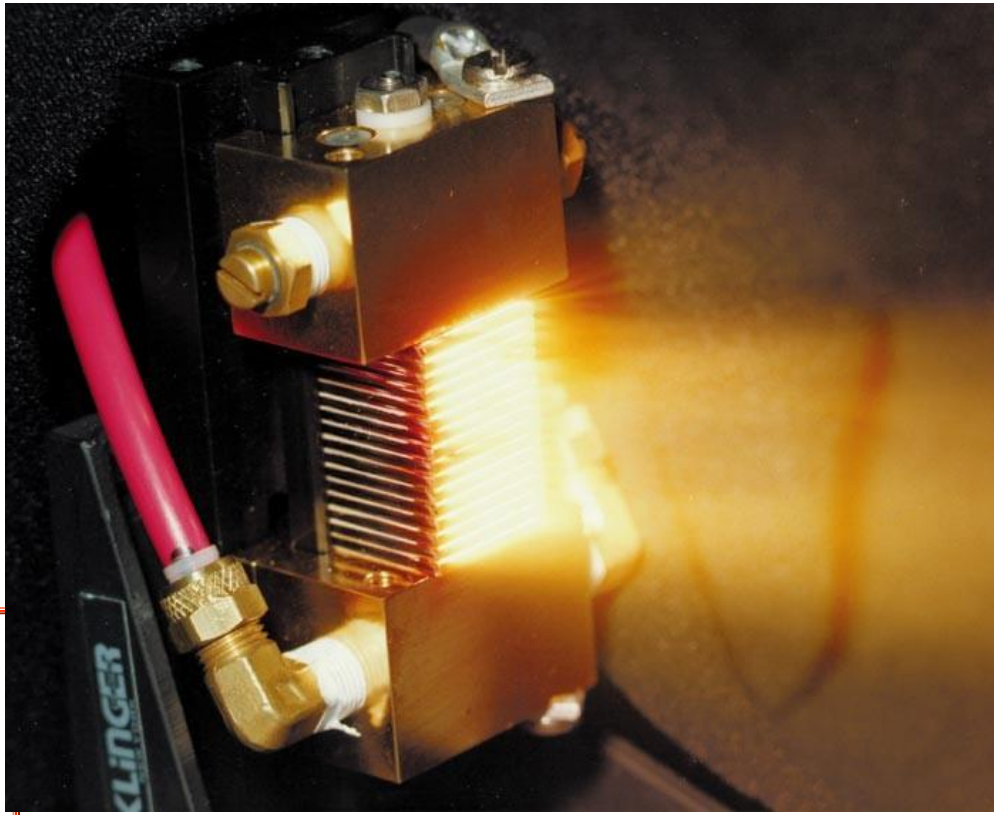




Epitaxial Growth

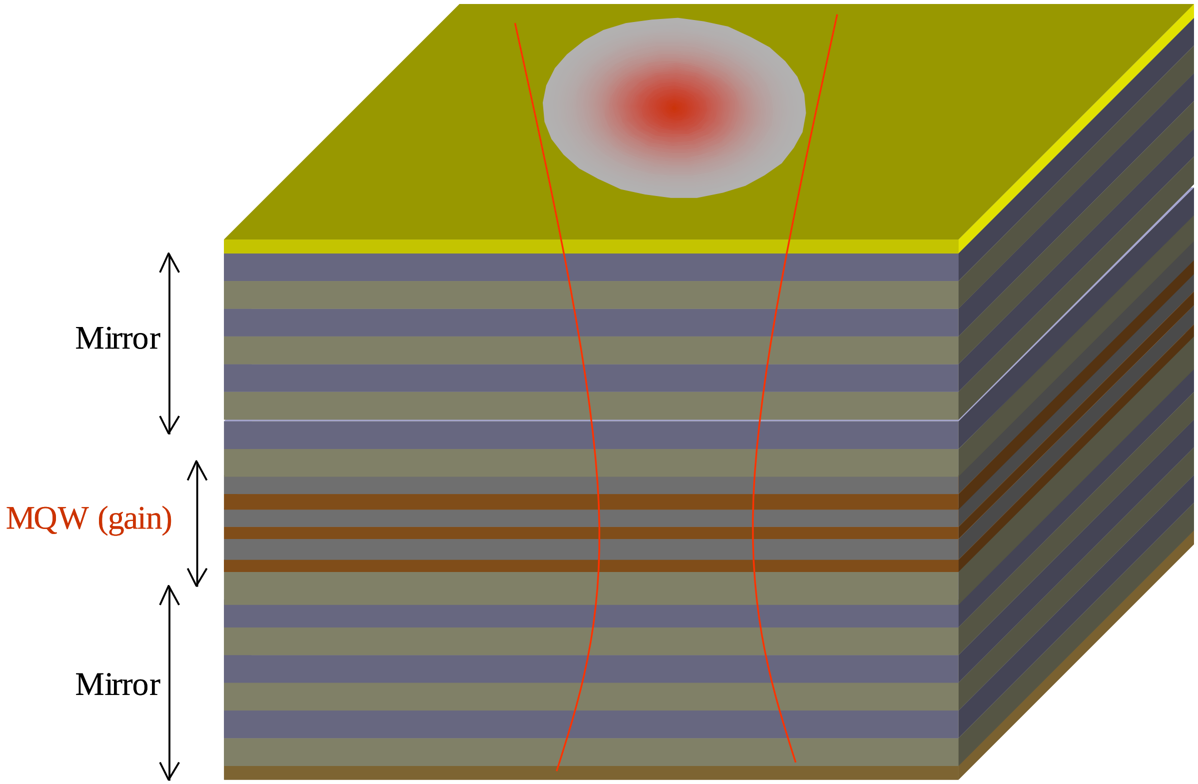
High Power Diode Bars





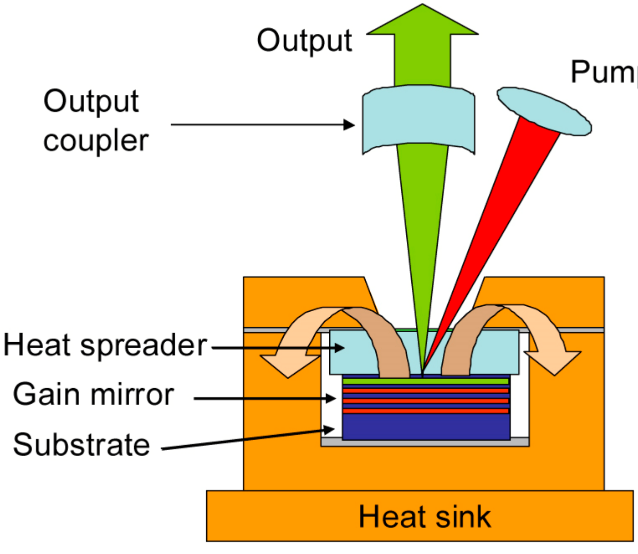
- P>100 W (cw)
- Diode-pumping solid-state lasers (DPSS)
- Material Processing
- …

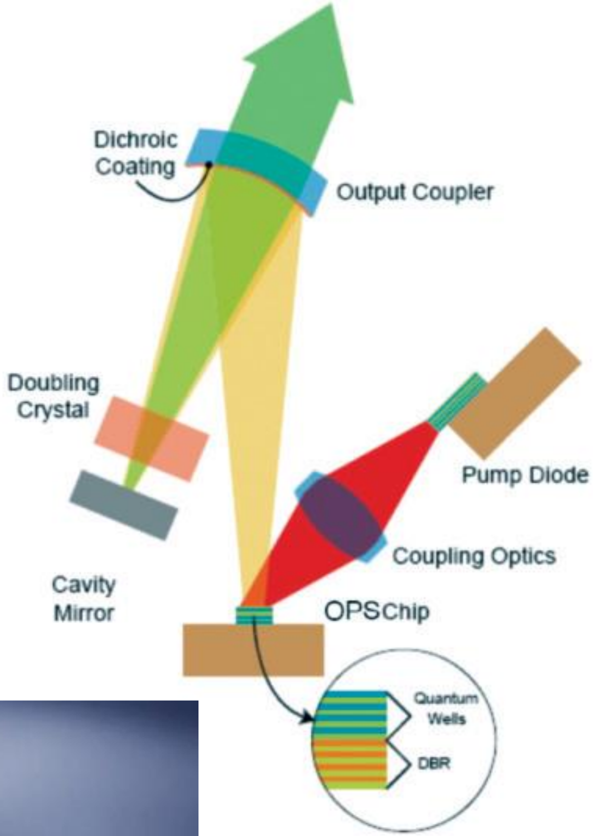
Vertical Cavity Surface Emitting Lasers (VCSEL)

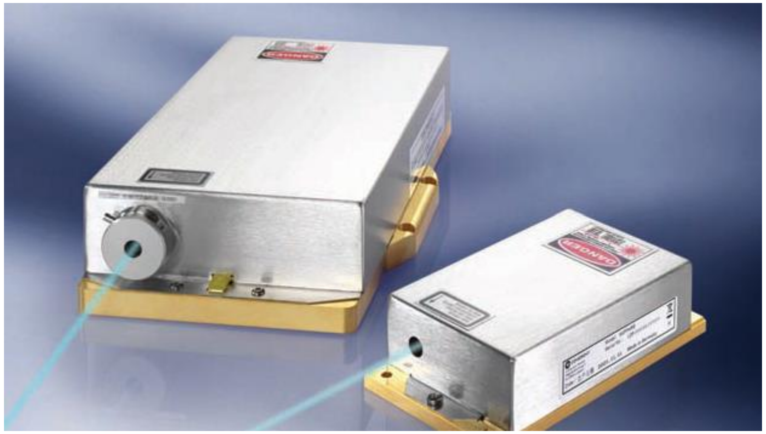


- Good mode quality couples to fiber efficiently for telecom applications
- Single mode operation
- 2-D structures cam be made
- Low power

Optically-Pumped Semiconductor Lasers (OPSL)







Laser Diodes Cover the Spectrum

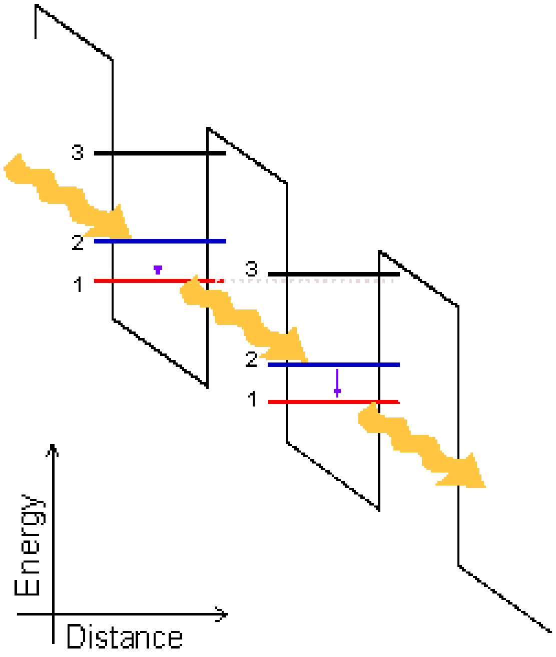
Compound	Spectral Region	Notes
$Al_xGa_{1-x}N$ **GaN** **$In_xGa_{1-x}N$**	*uv* *uv (350 nm)* *blue (480-400 nm)*	 data storage, display
$Ga_xI_{1-x}P$ (x=0.5) **$Ga_xAl_{1-x}As$ (x=0-0.45)**	*670 nm* *620-895 nm*	display
GaAs **$In_xGa_{1-x}As$ (x=0.2)**	*904 nm* *980 nm*	diode pumping solid-state and fiber lasers.
$In_xGa_{1-x}As_yP_{1-y}$ **(x=0.73, y=0.58)** **(x=0.58, y=0.9)**	*1100-1650* *1310 nm* *1550 nm*	Telecom

PbSSe	*4200-8000 nm*	cryogenic
PbSnTe	*6300-29,000 nm*	cryogenic

12.5 Recent Advances: Quantum Cascade Lasers

Original concept and theoretical prediction

R. F. Kazarinov and R. A. Suris, Fiz. Tekh. Poluprovodn, ***5****, pp. 797-800, (1971).*

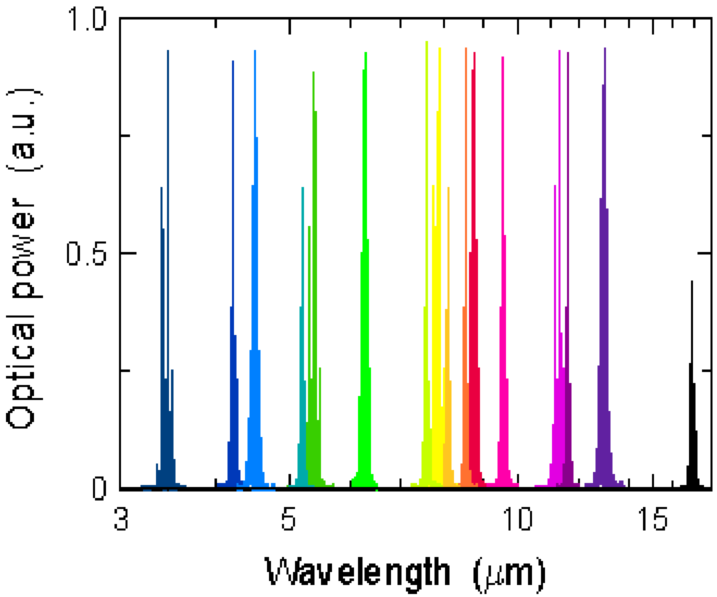


- Energy levels of electrons (3,2,1) in quantum wells strongly depend on layer thickness
- Laser photon created by an electron jumping between energy levels 1 and 2

→ therefore wavelength is determined by choice of layer thicknesses

- Many photons created by an electron cascading through many quantum wells

Wide wavelength-range of QC lasers



QC lasers cover entire mid-infrared wavelength range (3.4 - 17 µm) by tailoring layer thicknesses of the same material

THE END !

"Mr. Osborne, may I be excused? My brain is full."