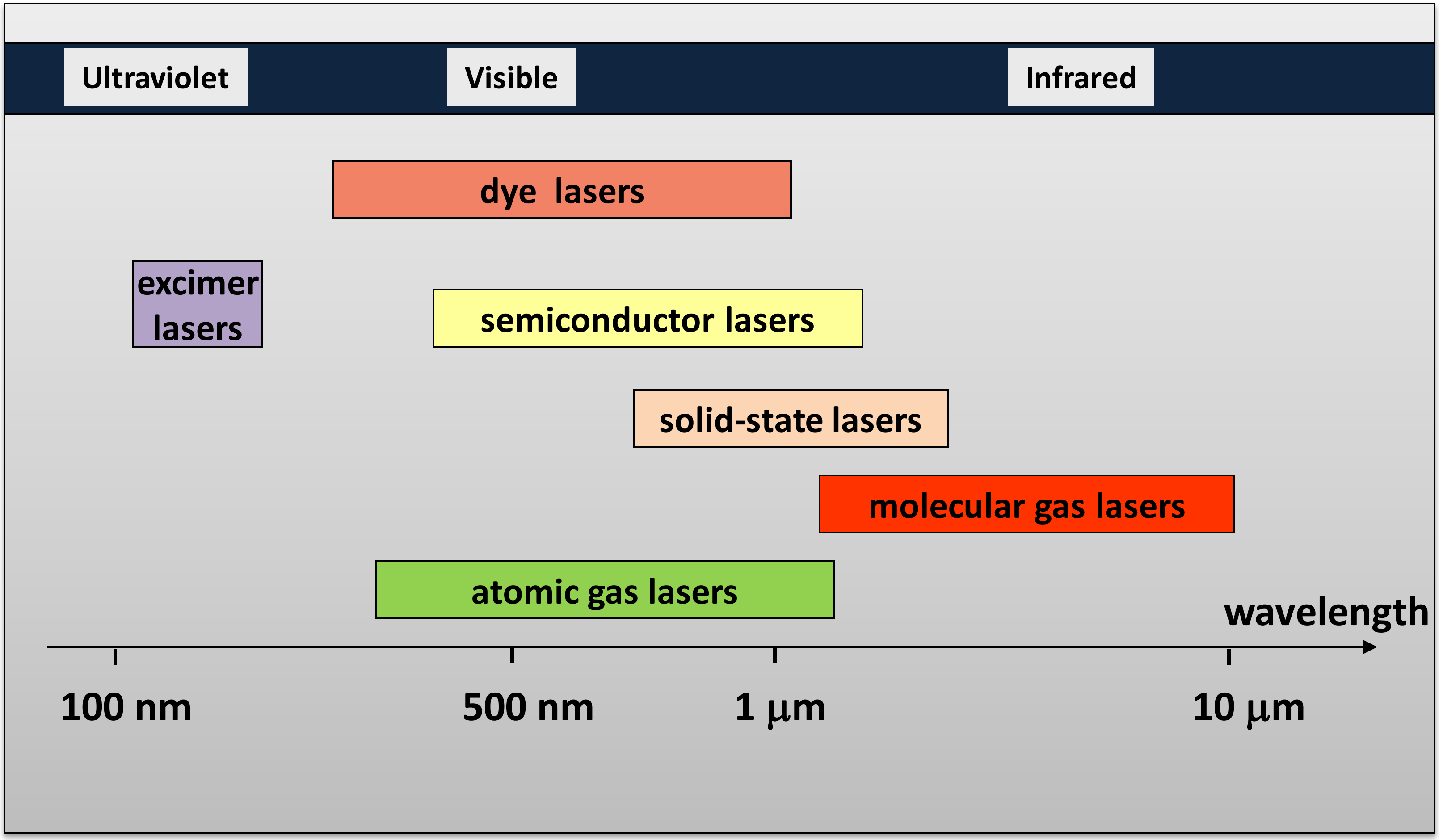
Examples of Specific Laser Systems

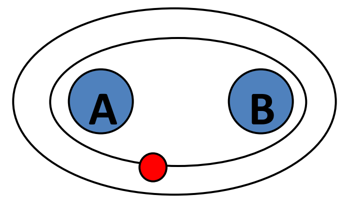
- Gas Lasers
  - CO_2 200+ kW
- Solid-State Lasers
  - Nd:YAG (15 kW)
- Fiber Lasers
  - Yb^{3+} (5+ kW)
- Dye Lasers
- Chemical Lasers
  - COIL (7+kW), MIRACL (>1 MW !!)
- Semiconductor Lasers

6.5 Active media and spectral ranges



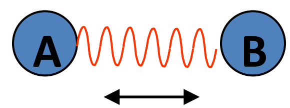
emission

electronic transitions



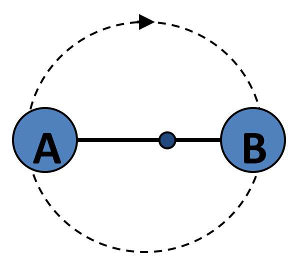
VIS, UV

vibrational transitions

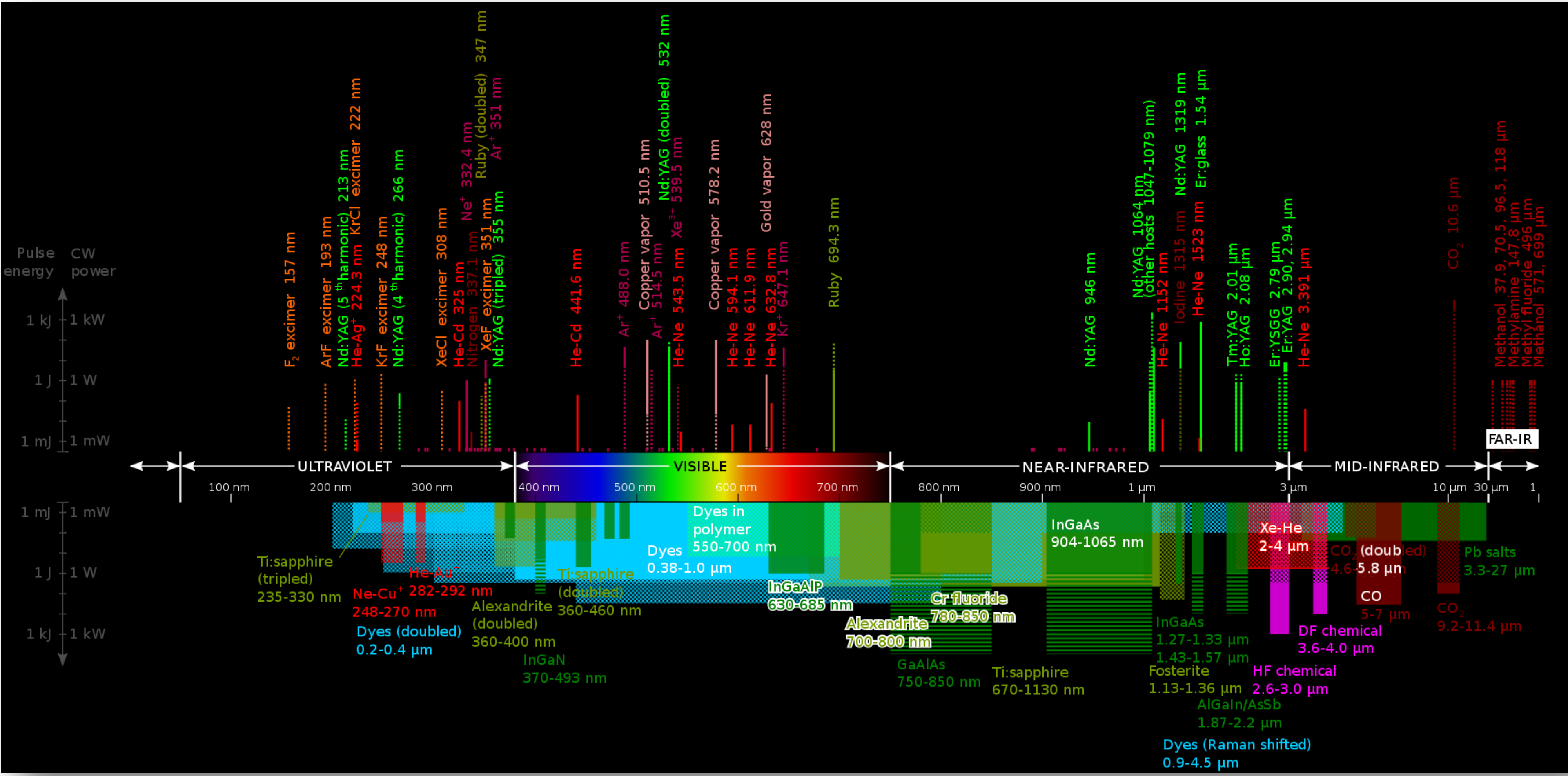


NIR, IR

rotational transitions



FIR



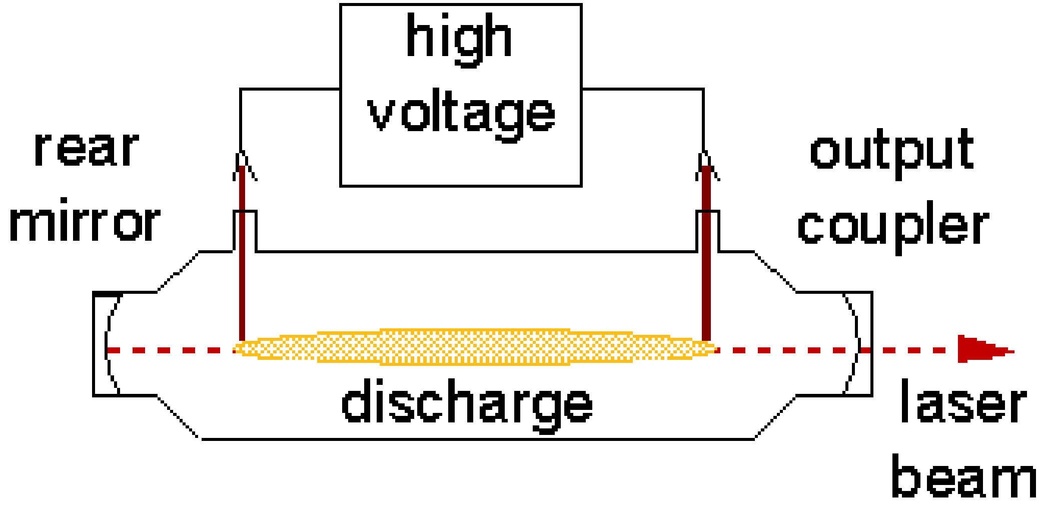
Pulse energy
CW power
1 kJ
1 kW
1 J
1 W
1 mJ
1 mW
ULTRAVIOLET
VISIBLE
NEAR-INFRARED
MID-INFRARED
FAR-IR
100 nm
200 nm
300 nm
400 nm
500 nm
600 nm
700 nm
800 nm
900 nm
1 μm
3 μm
10 μm
30 μm
F2 excimer 157 nm
ArF excimer 193 nm
Nd:YAG (5th harmonic) 213 nm
He-Ag+ 224.3 nm
KrCl excimer 222 nm
KrF excimer 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
Ruby (doubled) 347 nm
Ar+ 351 nm
Nd:YAG (tripled) 355 nm
He-Cd 441.6 nm
Ar+ 488.0 nm
Copper vapor 510.5 nm
Ar+ 514.5 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%

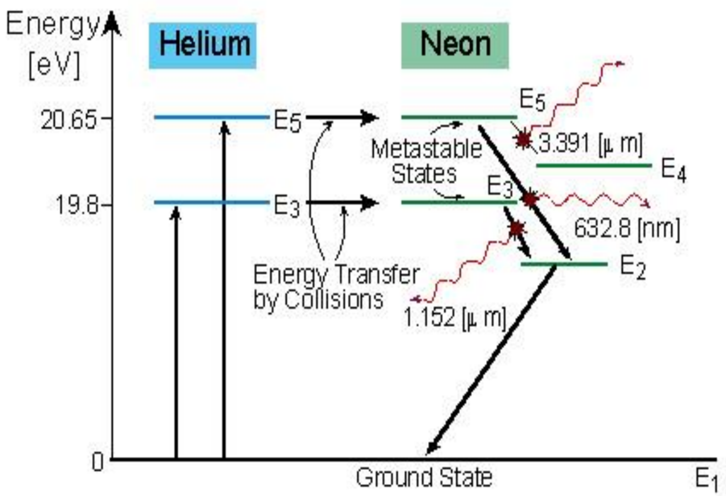
Gas Lasers

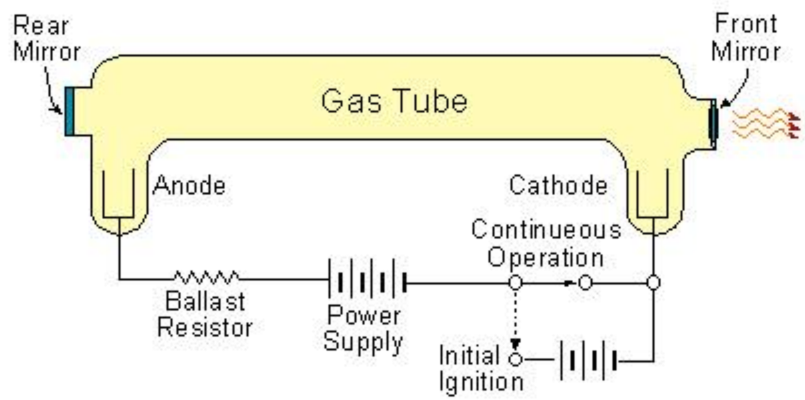


The excitation mechanism in most gas lasers is via *electric discharge*

The first Gas Laser: He-Ne

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





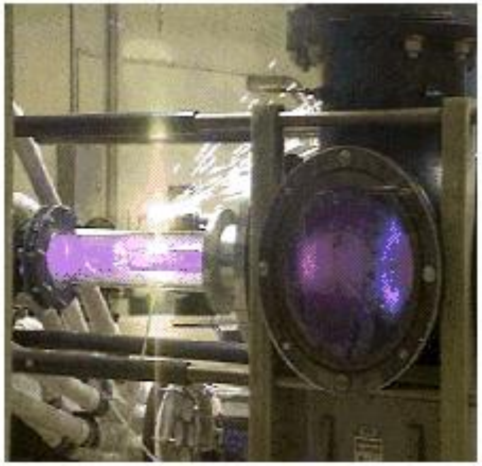
- The second working LASER system to be demonstrated.
- The first gas LASER to be produced.
- The first LASER to produce a continuous output beam
- The active laser medium is a gaseous mixture of He & Ne atoms, in a roughly 10:1 proportion
- The gas is enclosed in a cylindrical quartz DISCHARGE tube

Comparison of Gas Lasers

Laser Type	*Linear Power Density W/m*	*Maximum Power W*	*Power Efficiency percent*
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

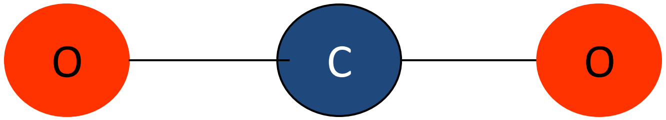


Applications (*pealing peanuts to star wars*)

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

11.2 Molecular Vibrations and Rotations

• Transitions are between molecular vibrational-rotational levels.

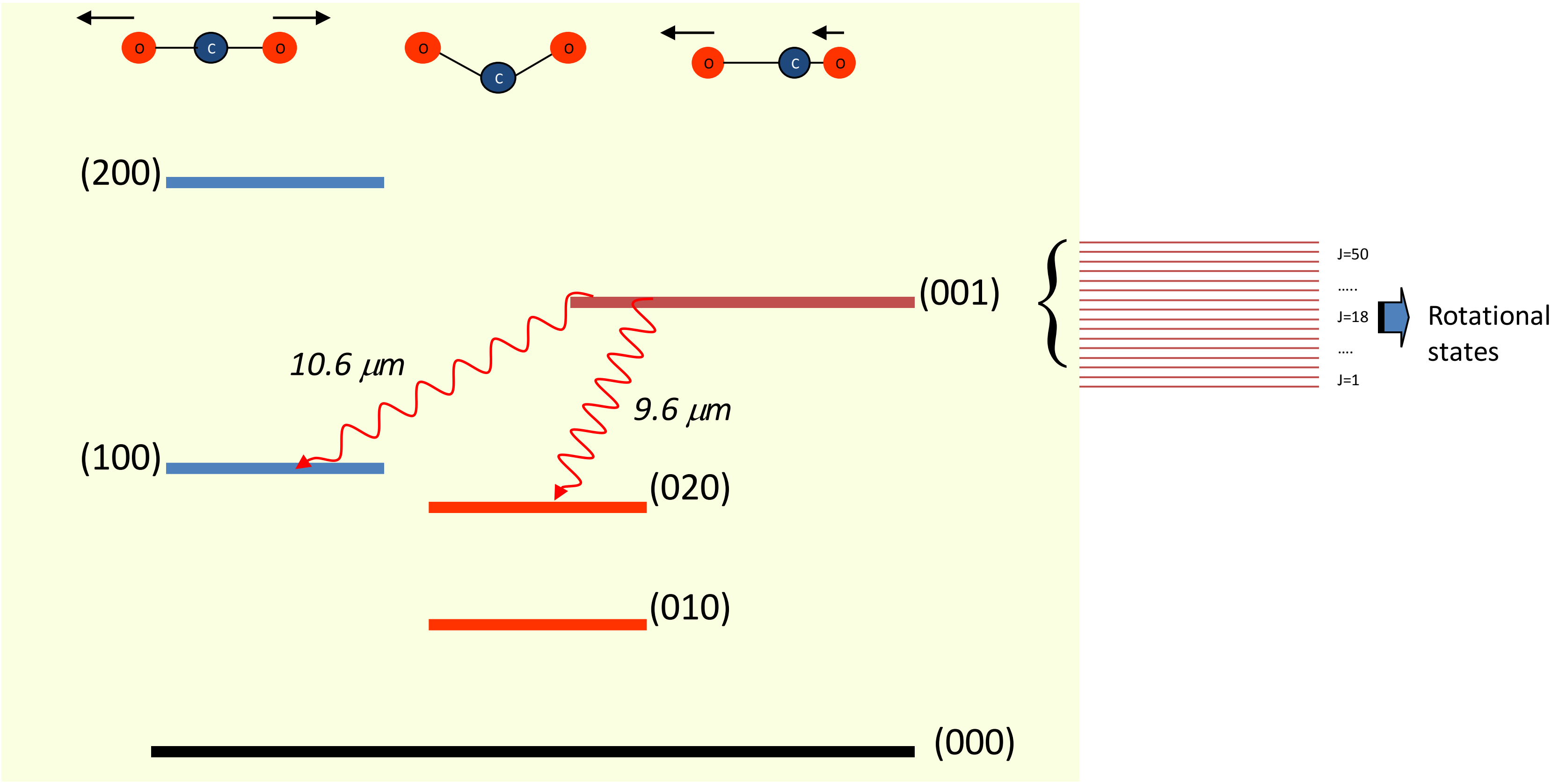


Modes of vibrations:

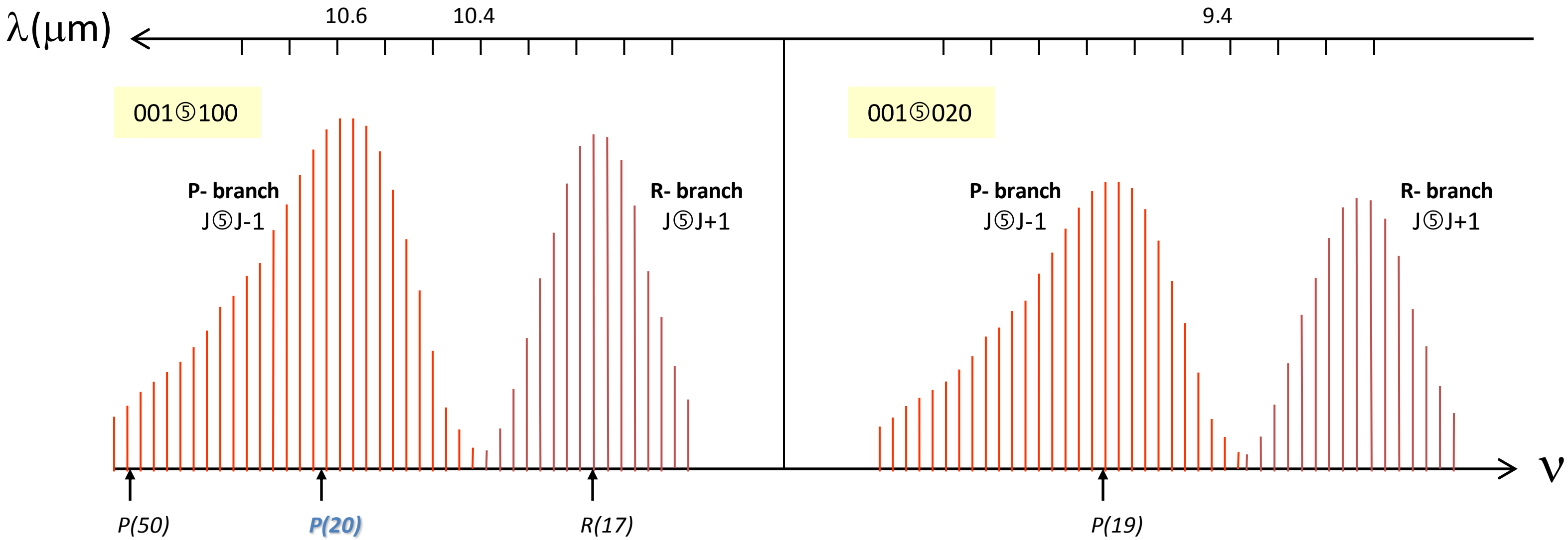
- Symmetric stretch
- Asymmetric stretch
- Bending mode

Simple Harmonic Oscillator (Quantum Mechanics):

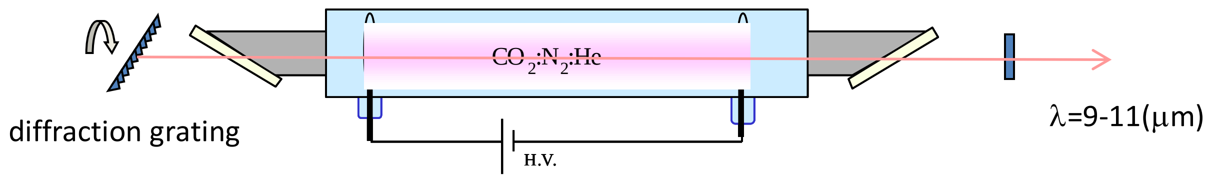
$$E(n_1,n_2,n_3)=h\nu_1(n_1+1/2)+h\nu_2(n_2+1/2)+h\nu_3(n_3+1/2)$$



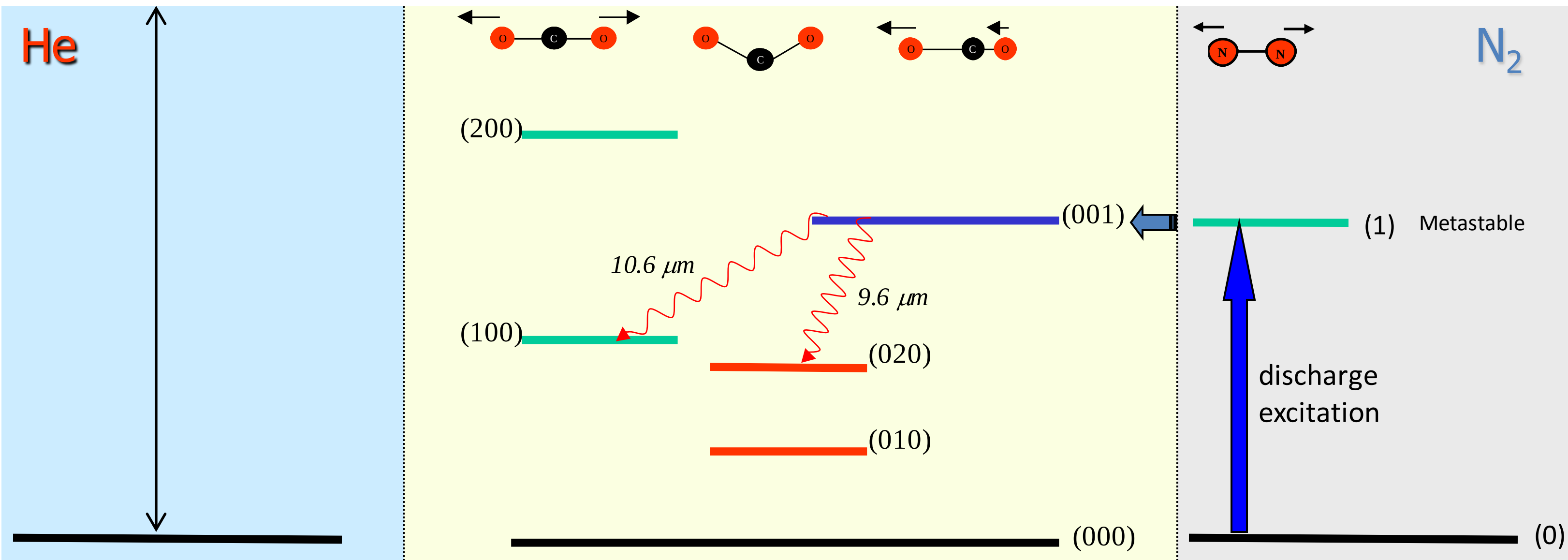
CO_2 Laser Transitions



Tuning:



Effect of Gas Mixtures: CO_2+N_2+He



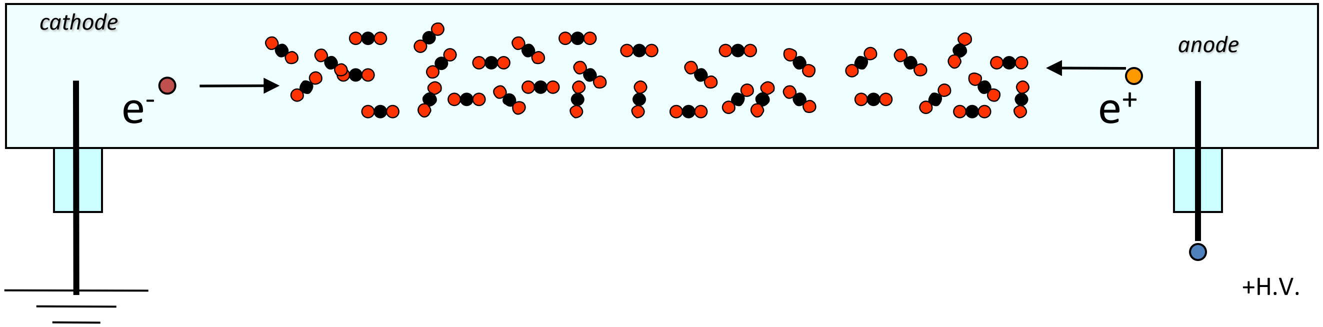
- Nitrogen helps populating the upper laser level in a discharge
- Helium helps to depopulate the lower laser level by collisions

Other possible additions to the gas mixture: CO, H_2

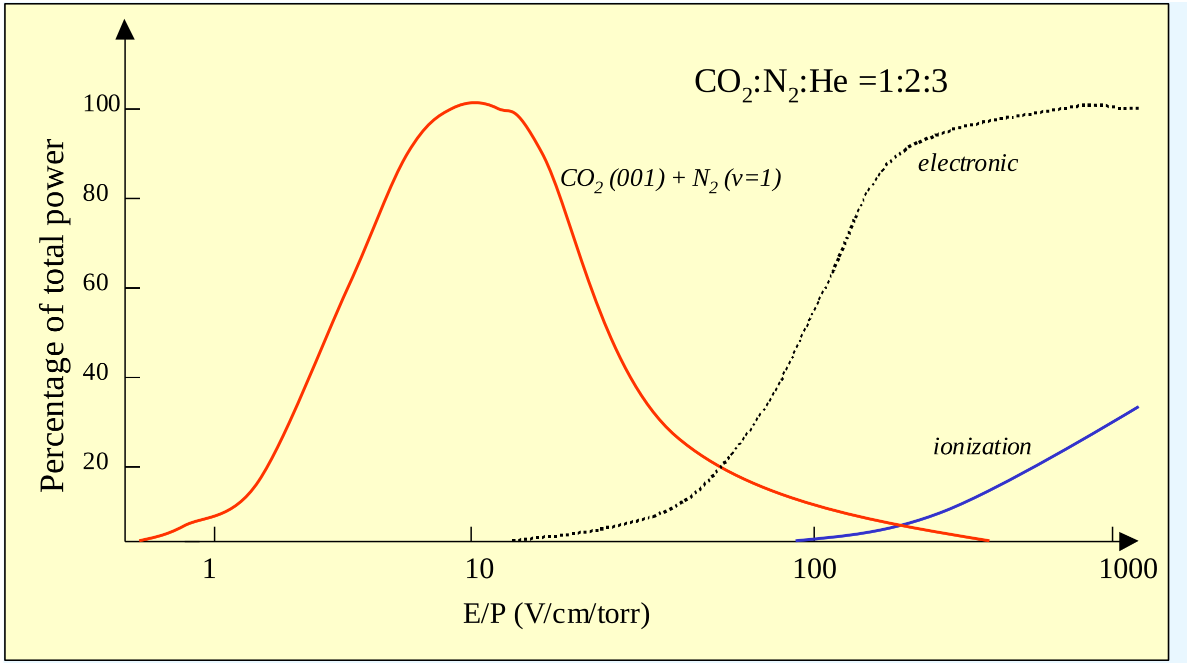
Typical Co_2:N_2:He Gas Ratios Recommended by Laser Manufacturers

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:

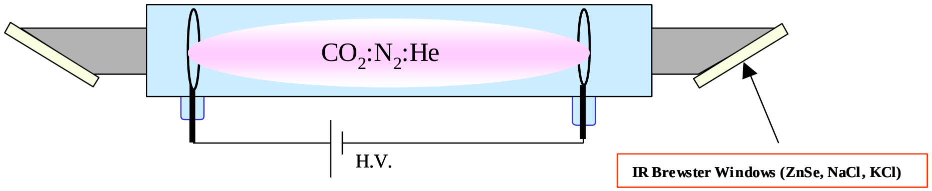
L=1 meter and P=25 torr

Need V=25 kV for optimum operation

11.4 Specific Types of CO_2 Lasers

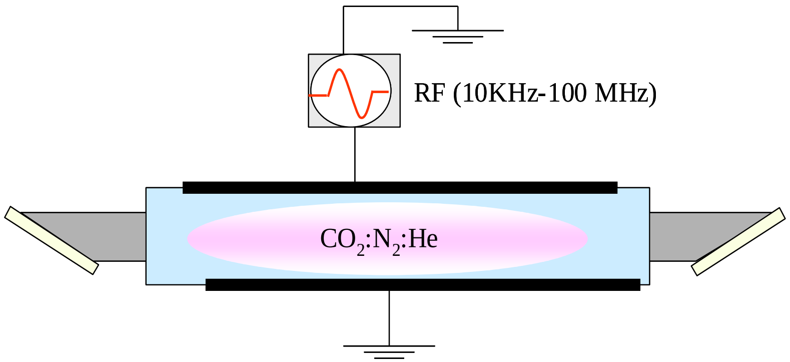
High Power CW Operation

❑ 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

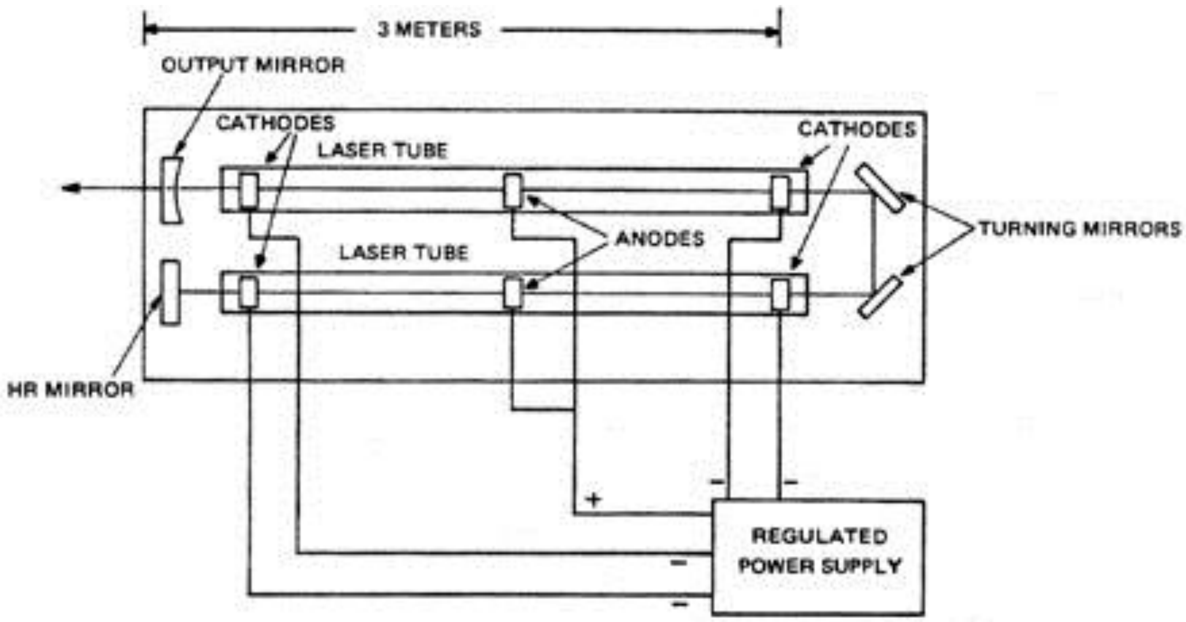
❑ RF-Discharge



- 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

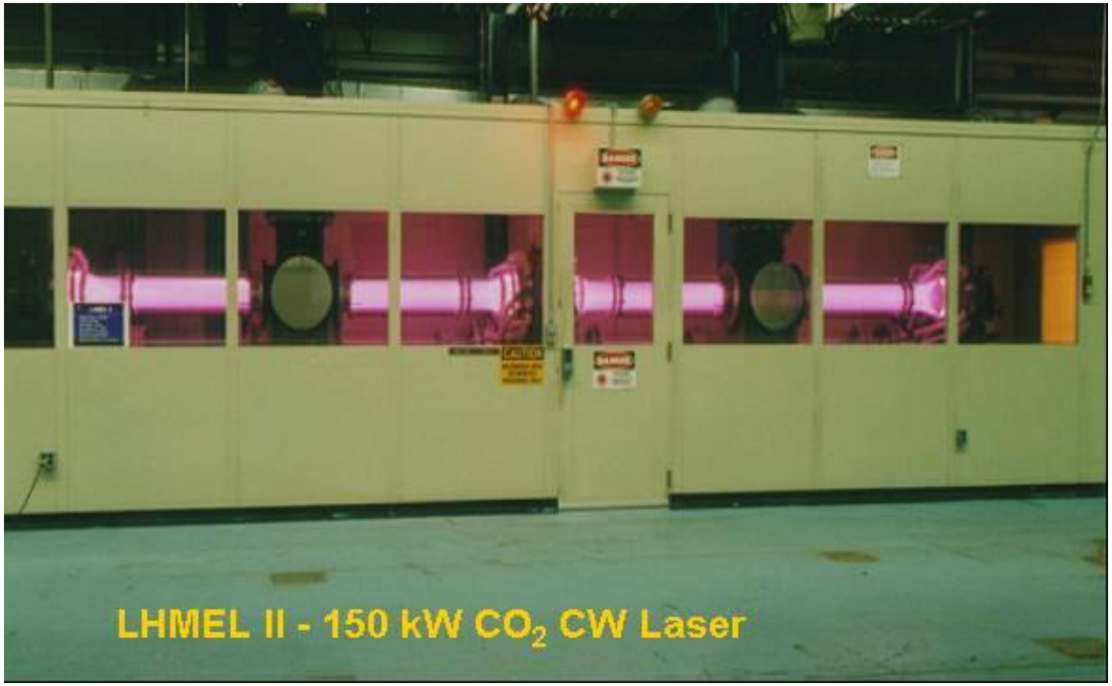
Example: A 250 W CW CO_2 Laser

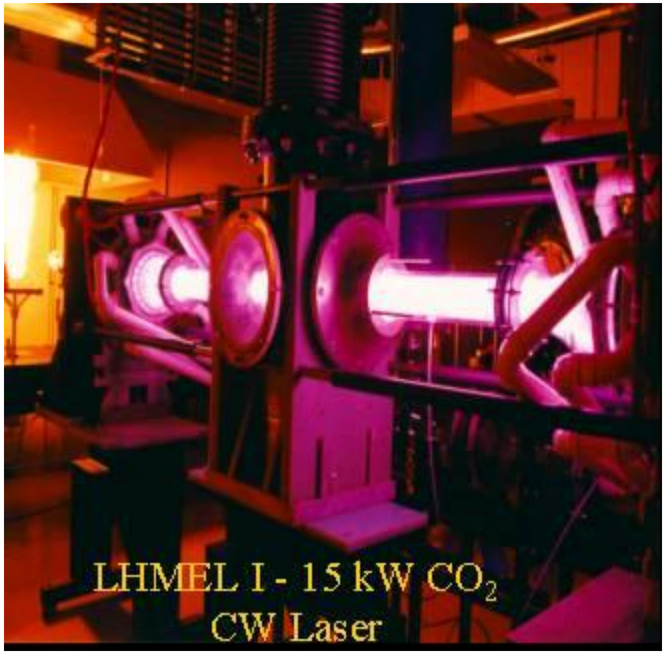


Operating Parameters of Commercial Class I CO_2 Lasers.

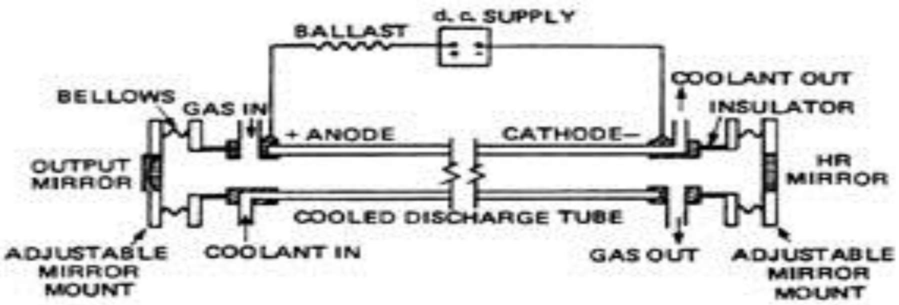
Active Length meters	Output Power watts	Gas Mixture CO_2:N_2:He	Gas Flow Rate liters/min	Power/ Length W/m	Water Flow Rate liters/min
1	50	1:1.5:9.3	1.15	50	2
2	100	1:1.5:9.3	1.15	50	2
5	275	2:1.35:9.3	4.01	55	10
6	375	1:8:23	4.26	62.5	10
9	525	1:6.7:30	4.23	58.3	10
18	1000	1:2.35:17	14.35	55.6	15

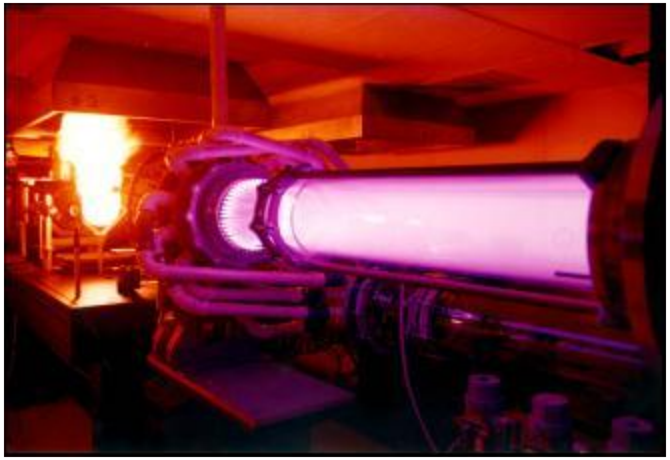
Laser Hardened Materials Evaluation Laboratory (LHMEL)
WP-AFB, Dayton, OHIO





Electric Discharge Coaxial Laser (EDCL)

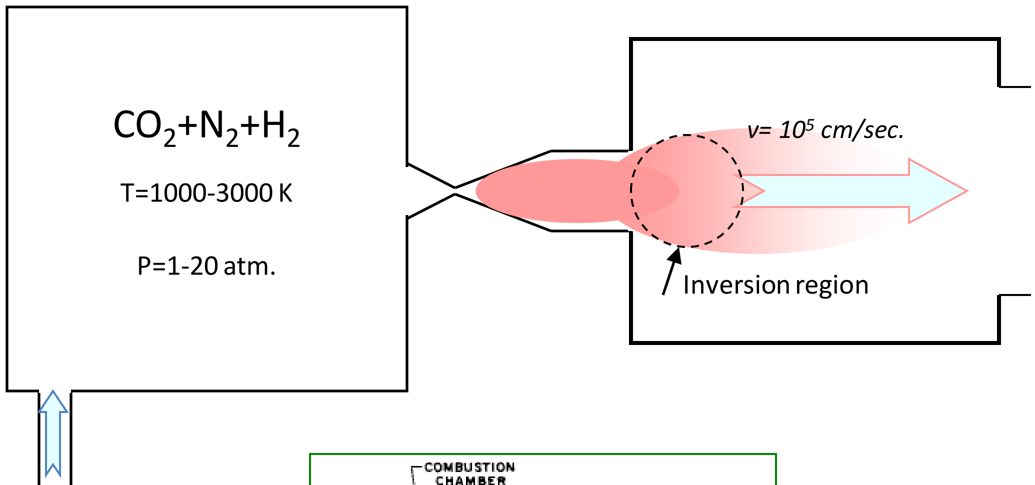


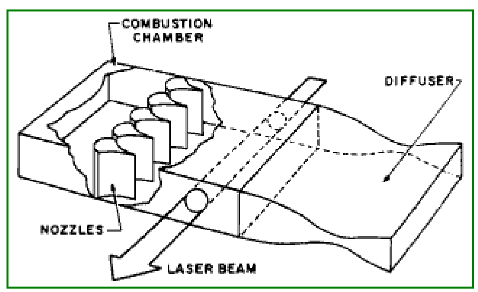


❑ Gas-Dynamic Lasers

Basov & Oraevskii (1963)

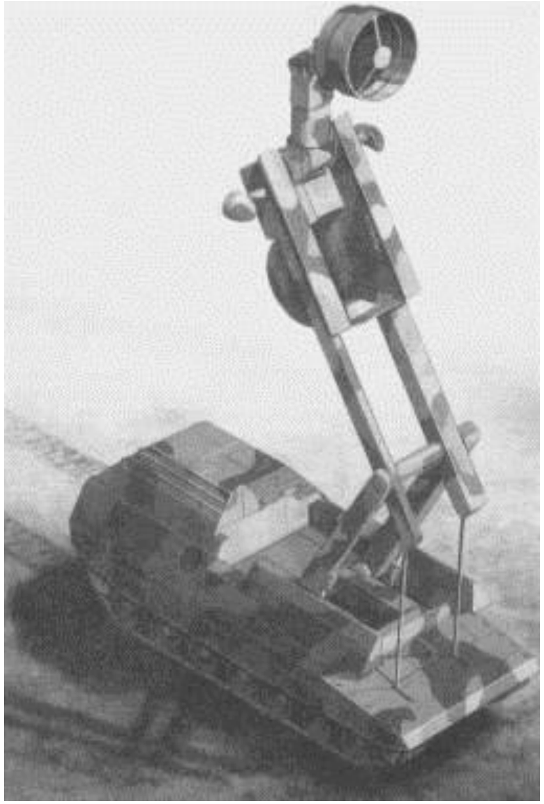
Principle: *Population inversion by rapid expansion (supersonic flow) of s super-heated gas*





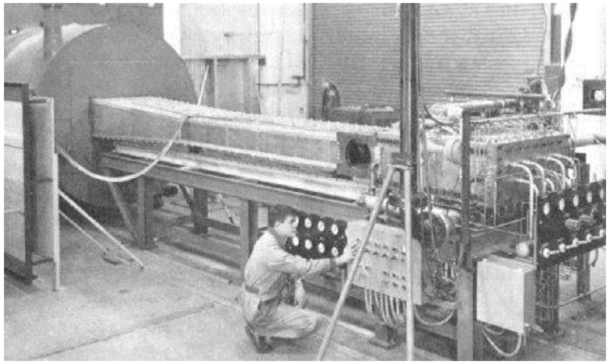
- cw powers up to 1 MW have been obtained from gas-dynamic CO_2 lasers !!

Gas-Dynamic Lasers

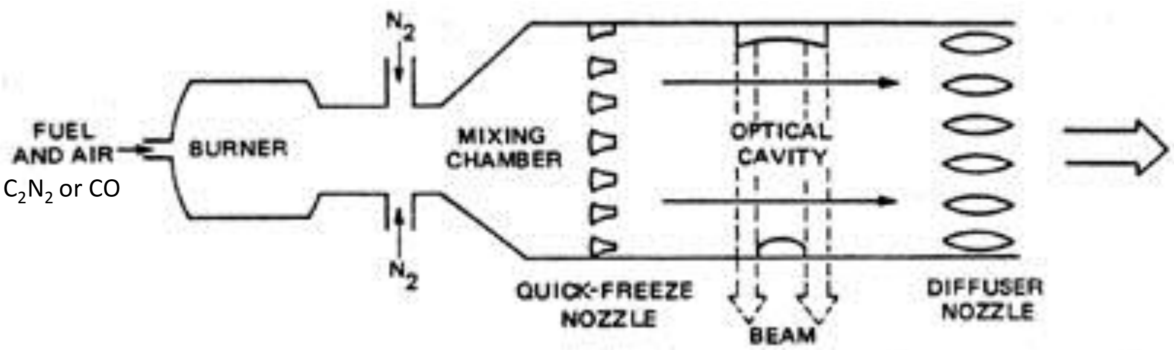


HELEX

High Energy Laser Experimental
Germany, 1970's

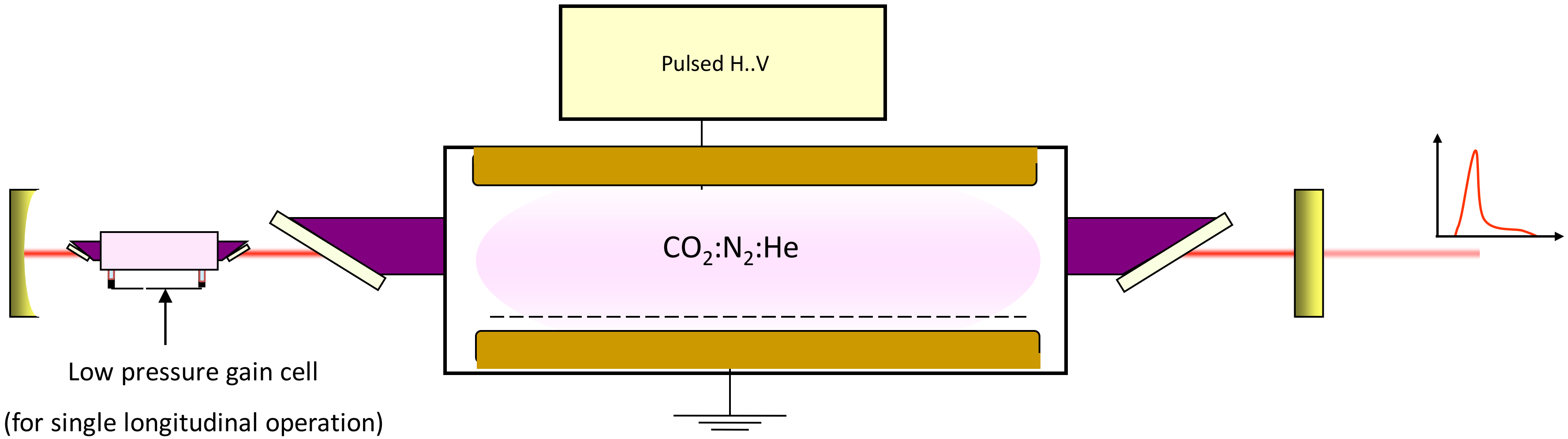


Large scale 135 Kilowatt gasdynamic laser at Avco Everett Research Lab.



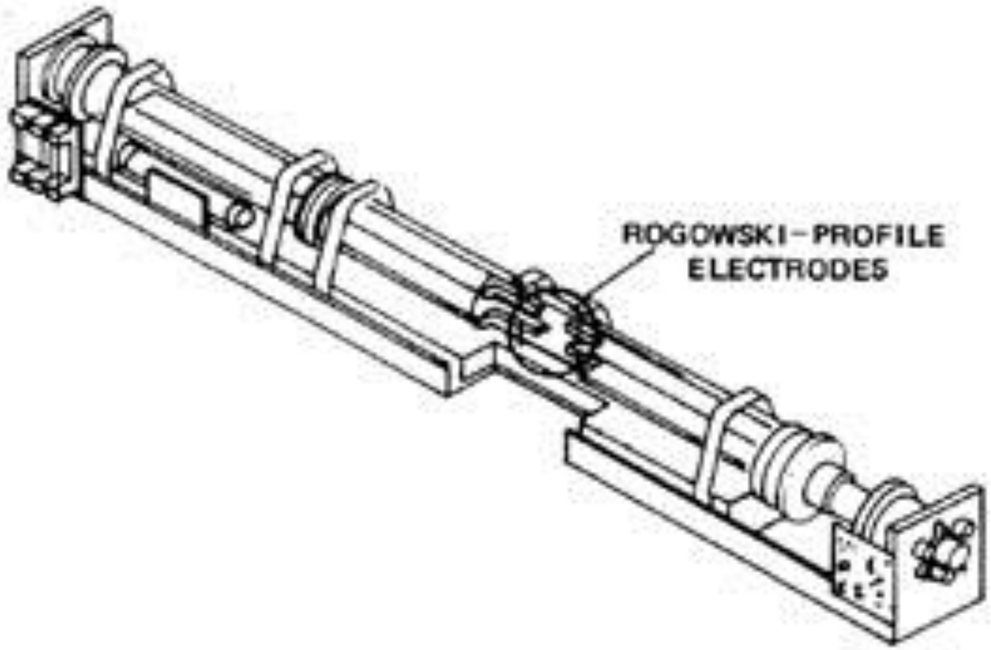
•Pulsed CO_2 Lasers

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

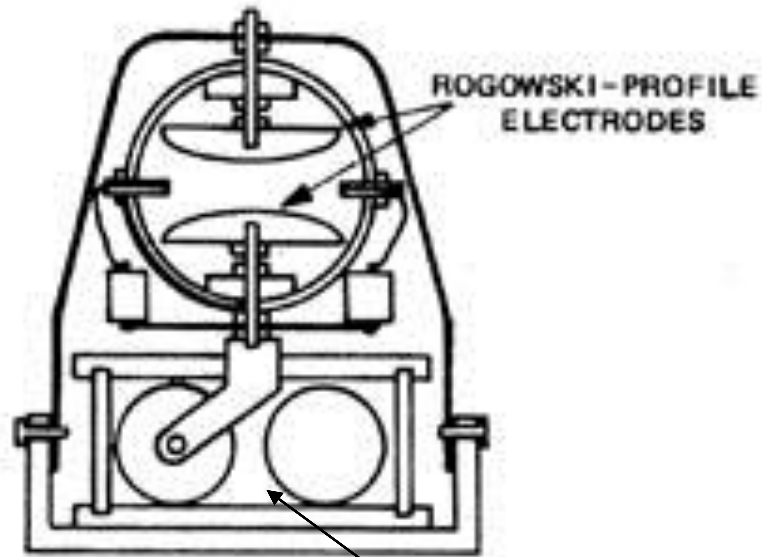


- Flowing or sealed systems
- Pulsewidths from 50 ns to 300 ns
- Repetition rates: 1Hz. to 1 kHz.
- Pulse energy: 50 mJ to 10 J (amplified)

Example

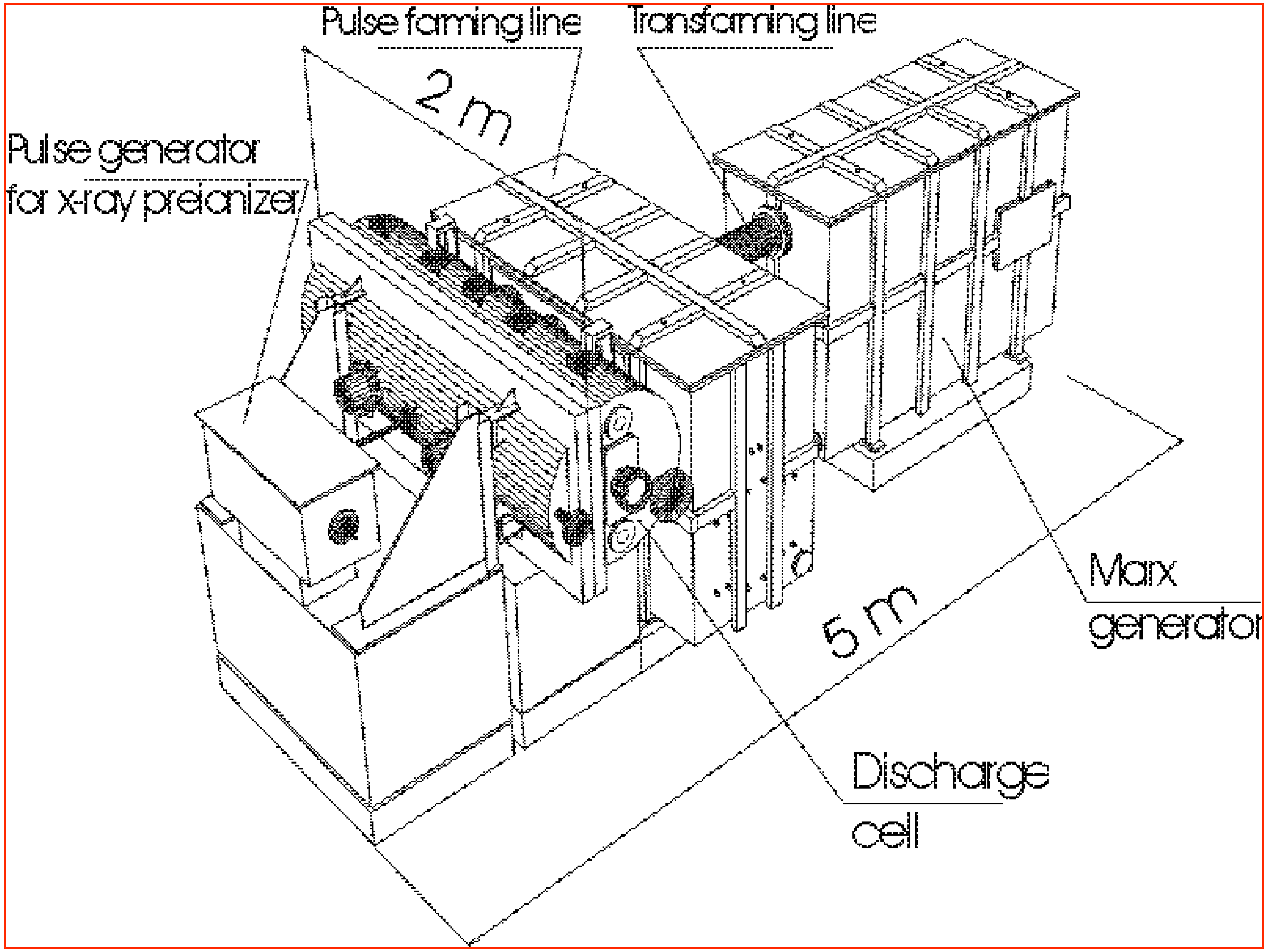


a. Perspective view

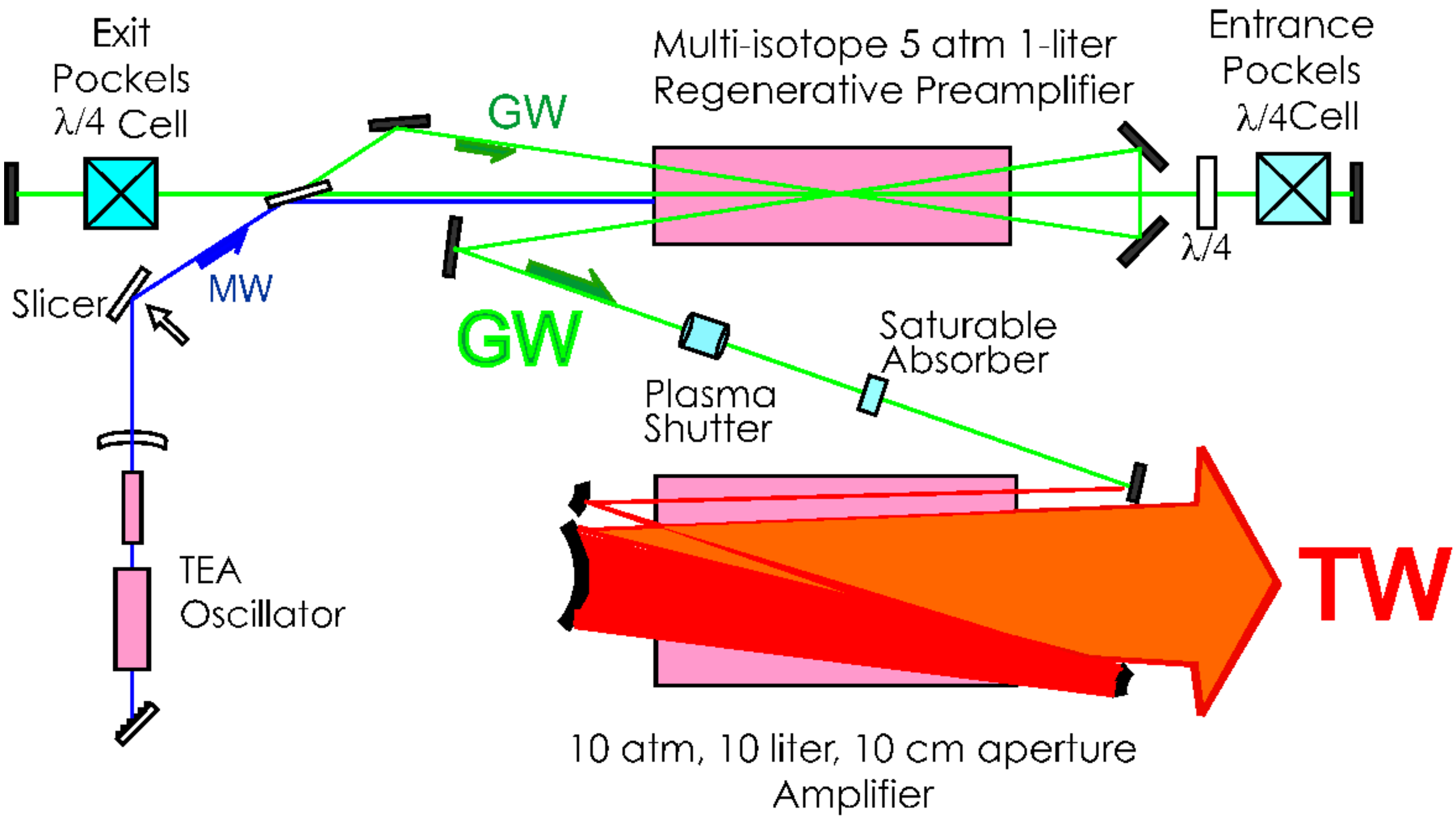


b. Cross-sectional view

Terra Watts Pulsed CO_2 Lasers



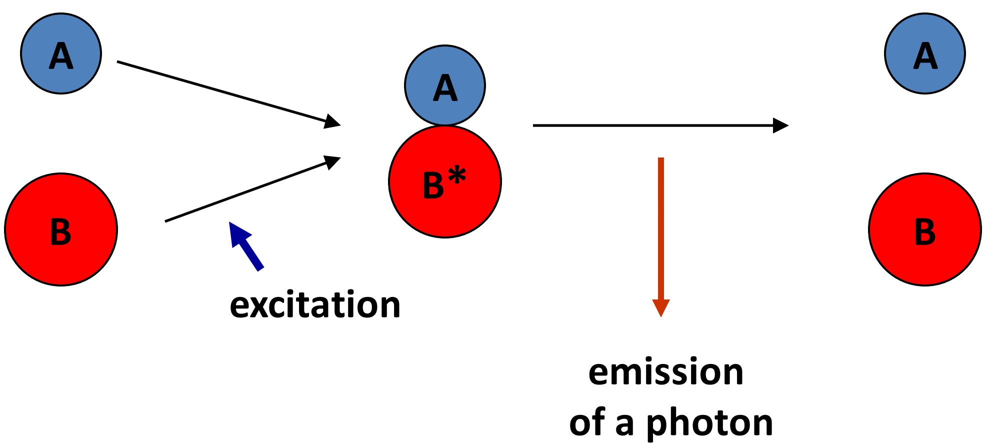
Picosecond TW CO_2 Laser at BNL



Excimer lasers: applications in lithography and eye surgery

molecules exist only in the excited state

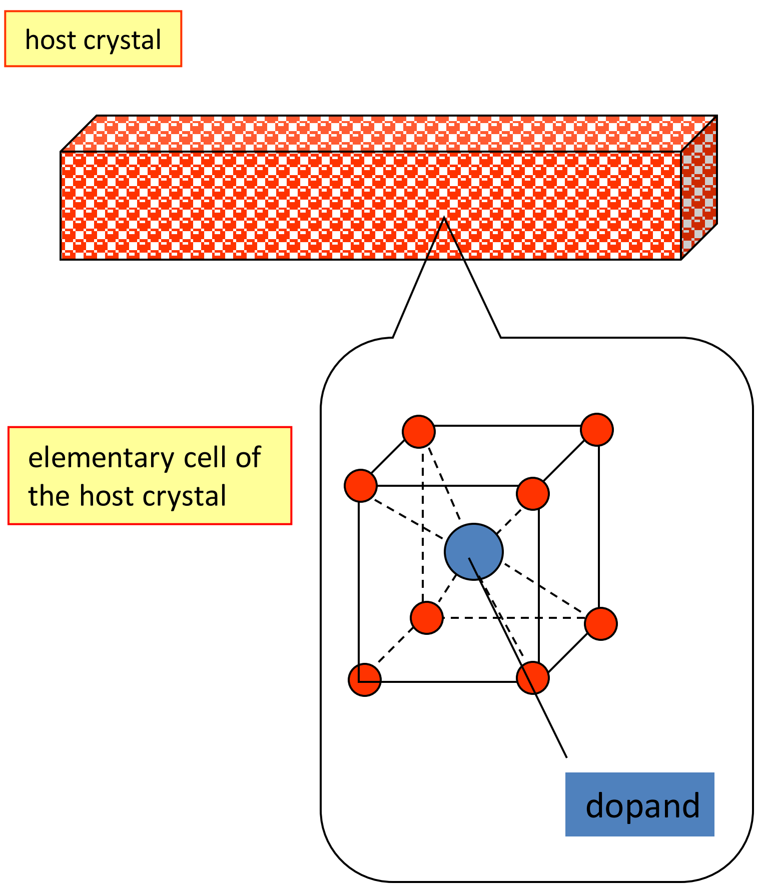
XeCl 308 nm
KrF 248 nm
ArF 193 nm
F_2 156 nm



10. Solid-state lasers

10.1 Introduction

The lasing atoms are fixed in a solid (crystal, glass). Solid-state lasers can operate in continuous (cw) or various pulsed modes.



Examples:

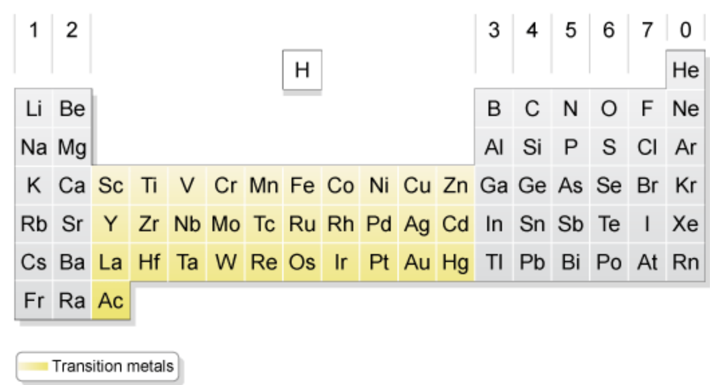
(a) Nd:YAG (yttrium aluminum garnett crystal doped with Nd atoms)
λ = 1.064 μm, 1.331 μm

(b) Nd:glass (glass doped with Nd:atoms)
λ = 1.062 μm (silicate glass)
λ = 1.080 μm (fused silica)

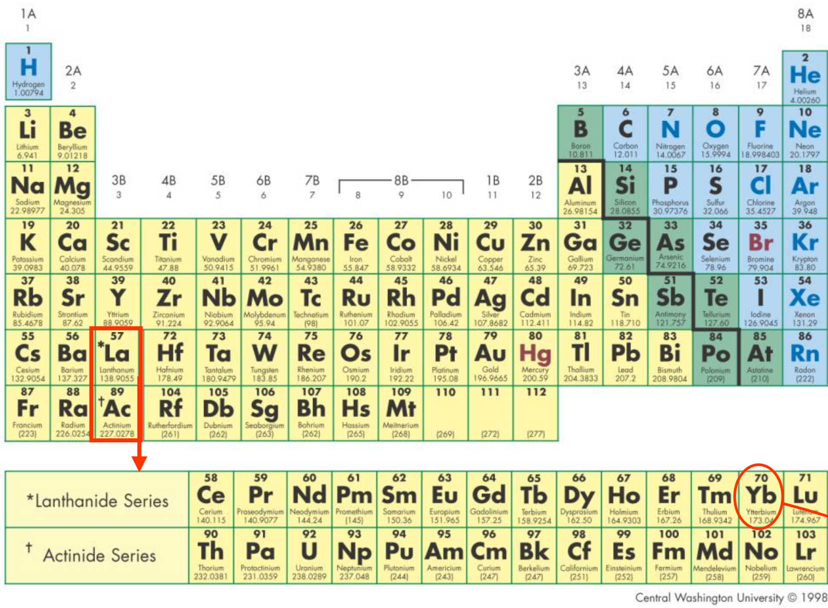
(c) Ti:sapphire λ = 0.7 - 1.1 μm

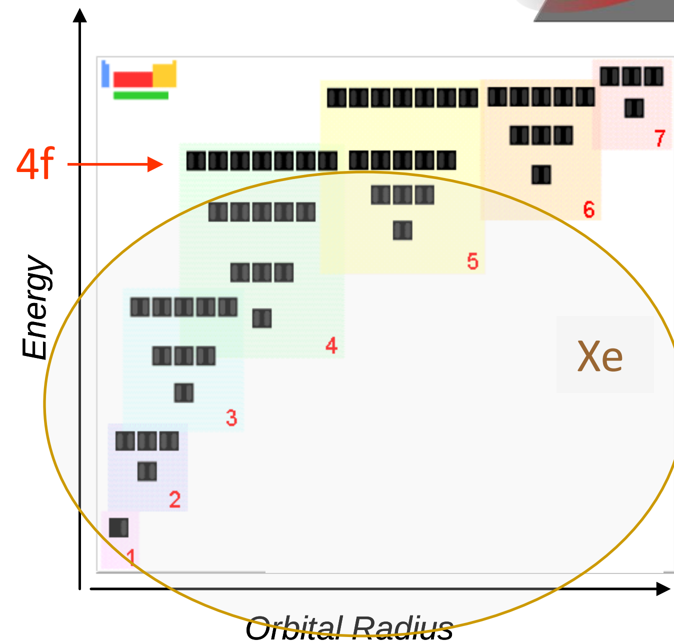
(d) Hm:YAG (holmium atoms doped into a YAG crystal)
λ = 2.1 μm

(e) color centers (intentionally created defects in a crystal)
λ = 1.5 - 3.5 μm (in different hosts)



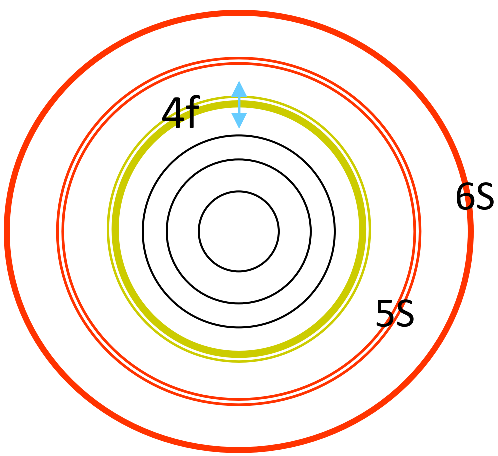
The 4f-4f transitions in Rare-Earths Ions:

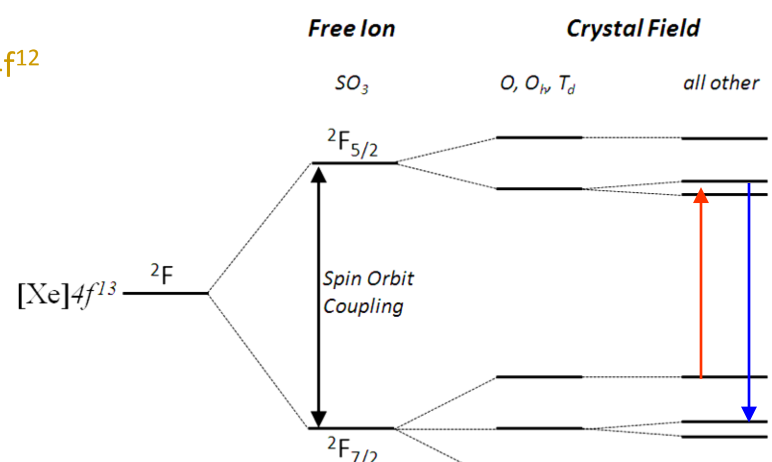




Yb ➡ (Xe)$4f^{13}6s^{2}$

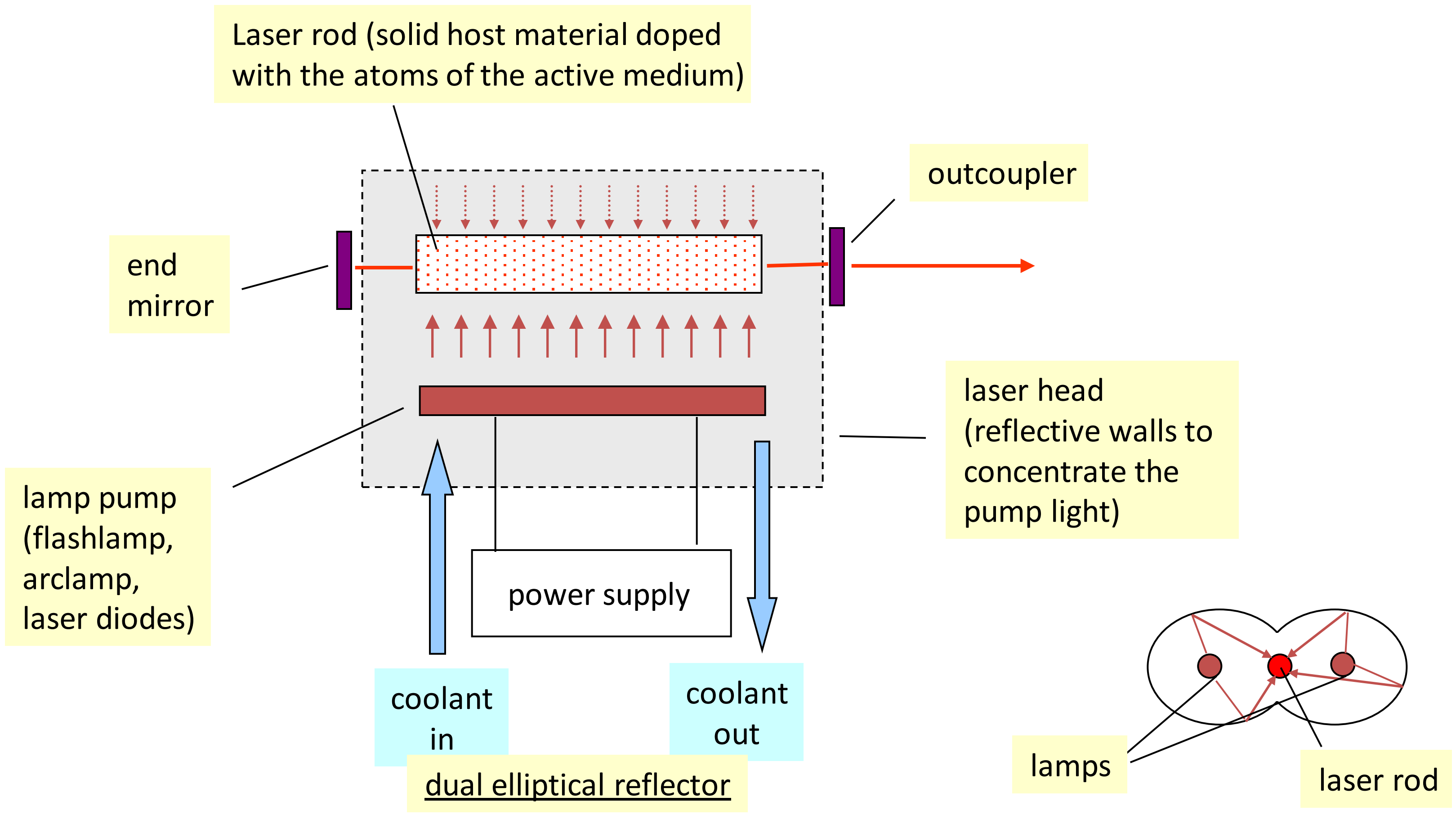
Yb^{3+} = (Xe)$4f^{12}$



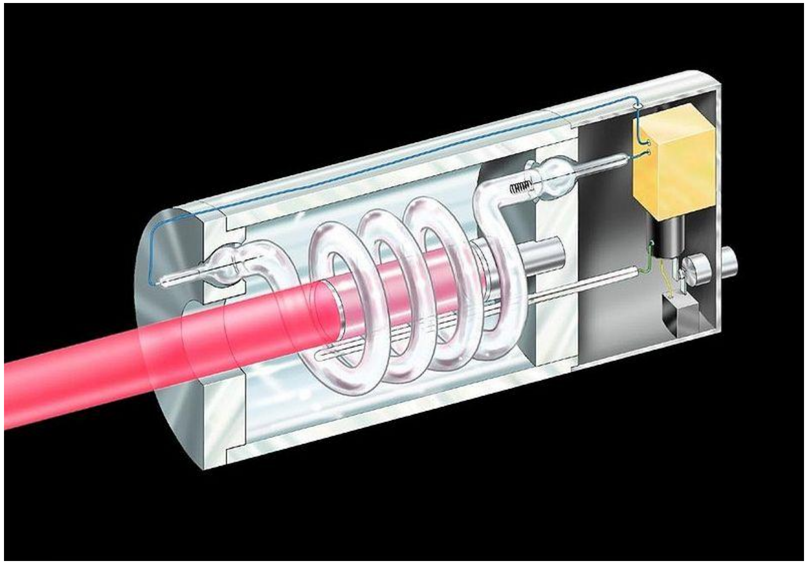


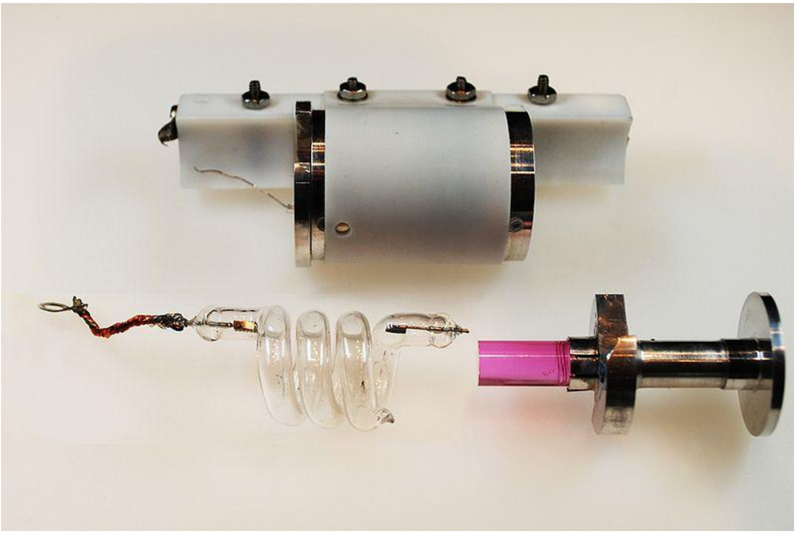
		He-Ne	Nd:YAG	$Ti{:}Al_2O_3$
	λ	633 nm	1064 nm	700 - 1000 nm
SSL: much smaller cross sections	σ	$3x10^{-13}$ cm^{-2}	4 x 10^{-19} cm^{-2}	4 x 10^{-19} cm^{-2}
SSL: much longer lifetimes	$\tau_2/\ \tau_1$	60 ns/10 ns	250 µs/~30 ns	3.2 µs/fast
SSL: much higher saturation intens.	I_{sat}	2 W/cm^2	2 kW/cm^2	200 kW/cm^2
SSL: much smaller quantum defect	$\frac{E_{laser}}{E_{pump}}$	$\frac{2\ eV}{20\ eV}$	$\frac{1.2\ eV}{1.5\ eV}$	$\frac{1.6\ eV}{2.3\ eV}$
SSL: much(!) wider gain spectra	$\Delta\omega$	2π x 1.5 GHz	2π x 200 GHz	2π x 100 THz
SSL: atom lifetime >> cavity lifetime	τ_c	200 ns	5 – 100 ns	5 – 100 ns
SSL: much higher number densities	N	1 torr $3x10^{16}$ cm^{-3}	1 at.%, $1.4x10^{20}$ cm^{-3}	0.5 wt.%, $1.7x10^{20}$ cm^{-3}

10.2 Layout of a solid-state laser



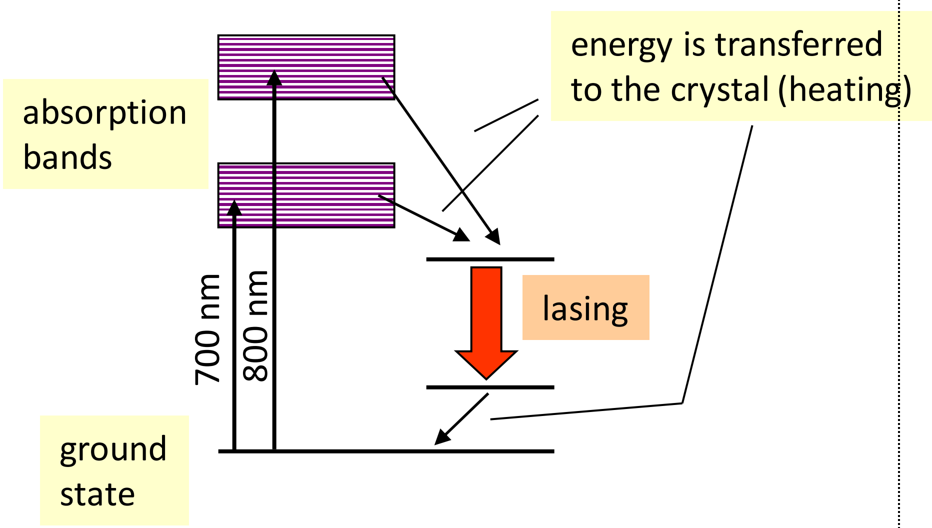
Maiman’s Ruby Laser





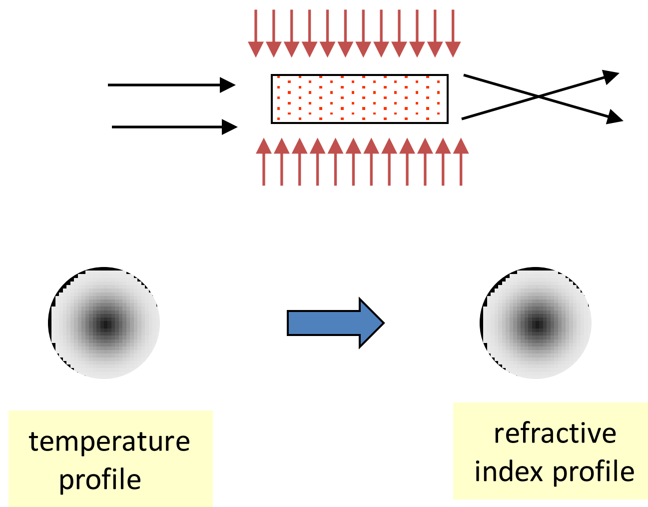
The most common solid-state laser is based on Nd atoms as dopands.

Energy diagram of Nd:



By changing the host material the laser wavelength and the thermal properties can be changed.

thermal effects:



Output (Nd:YAG)

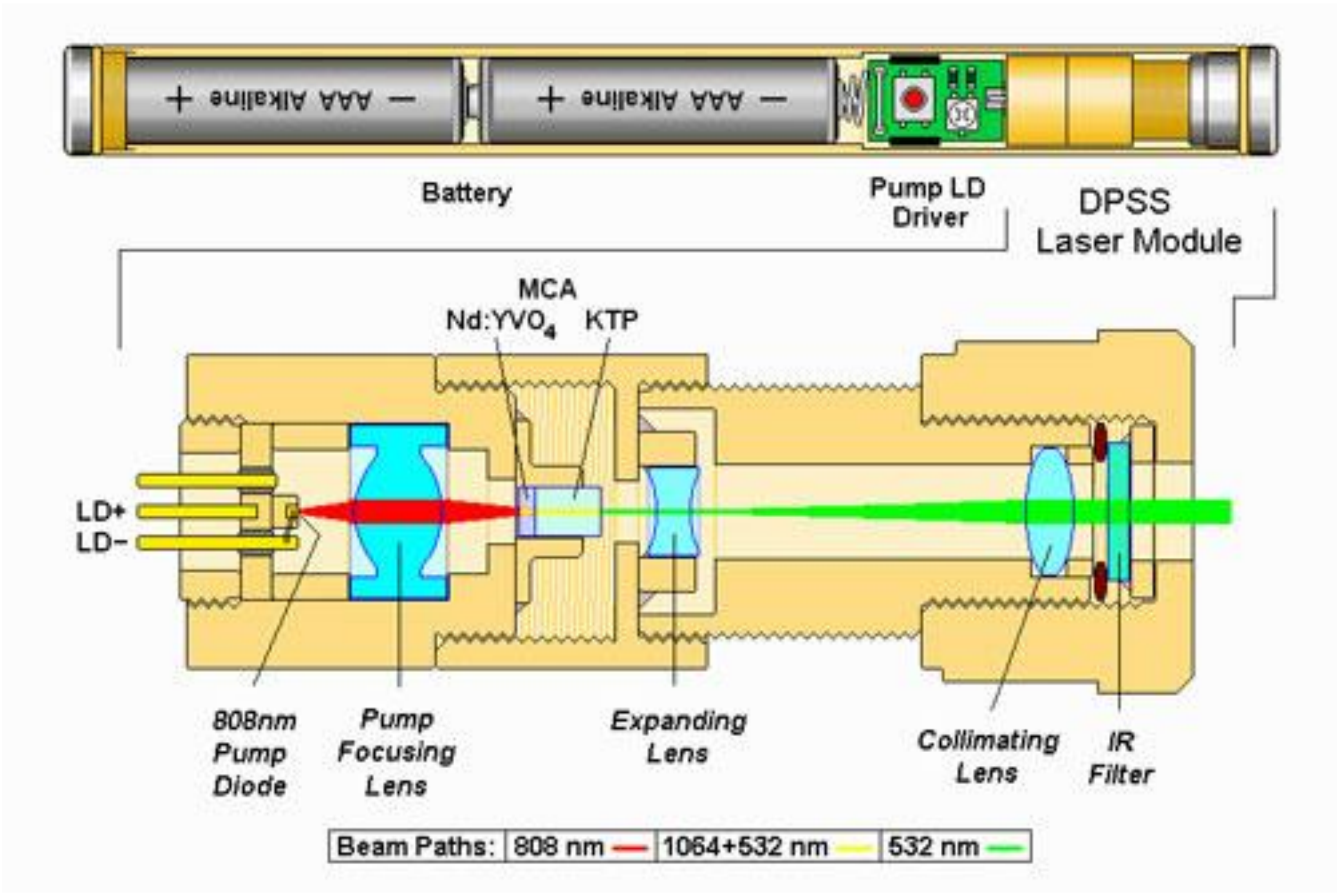
cw: $\leq$ 1000 W

pulsed: pulse energy $\leq$ 1 Joule

Q-switched - 10 ns pulse duration

modelocked - 100 ps pulse duration

Green Laser Pointer: a frequency doubled diode-pumped Nd:YVO_4 Laser!!



Titanium doped sapphire ($Ti:Al_2O_3$) laser

The jewel of ultrafast lasers!!

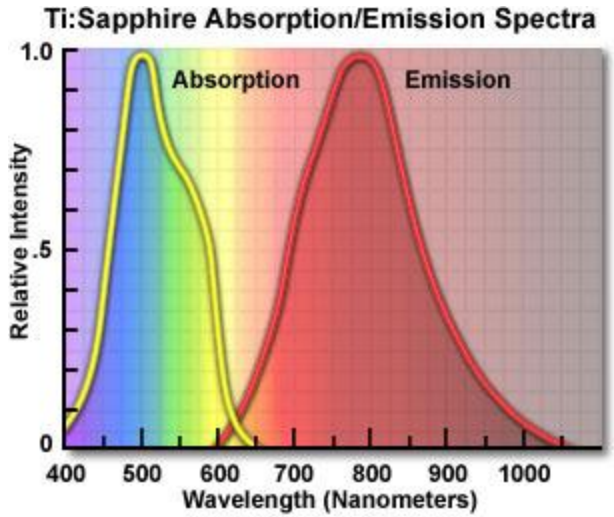
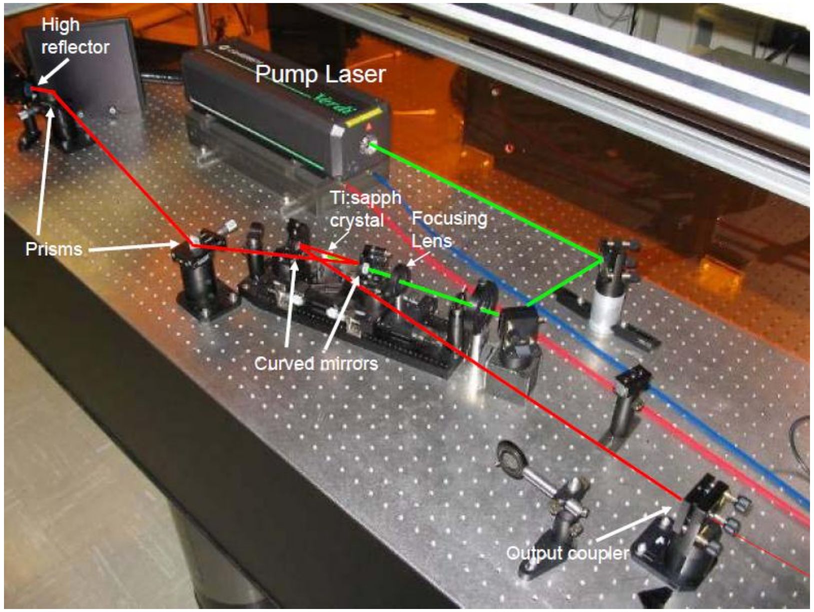
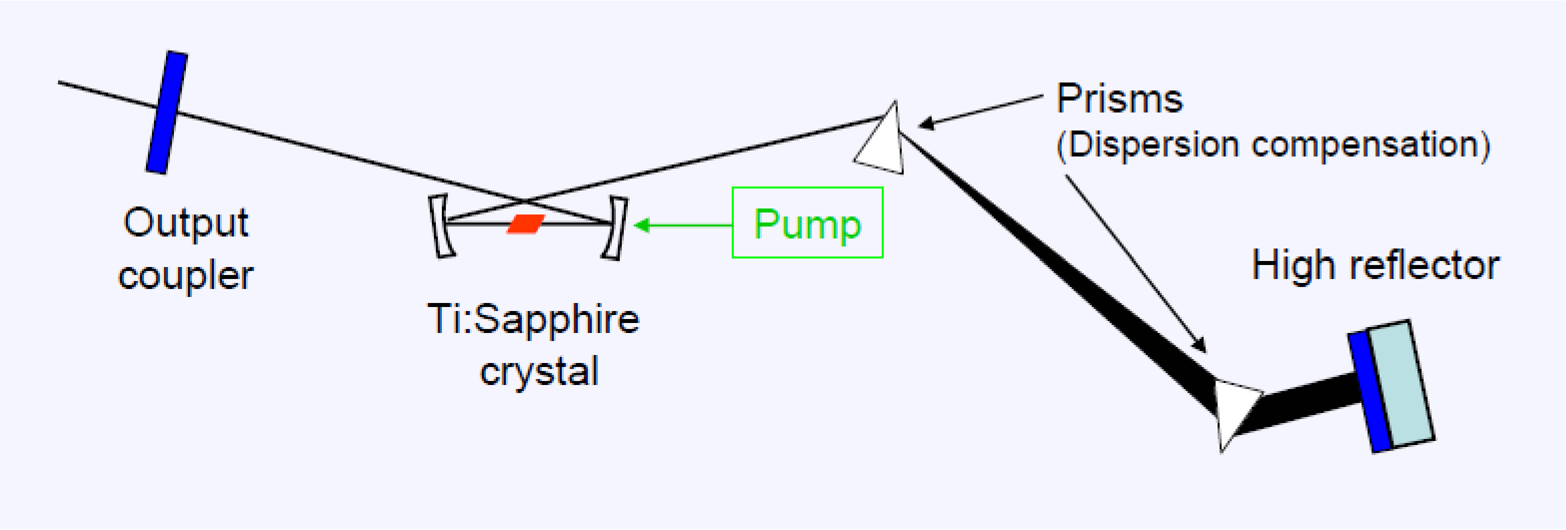
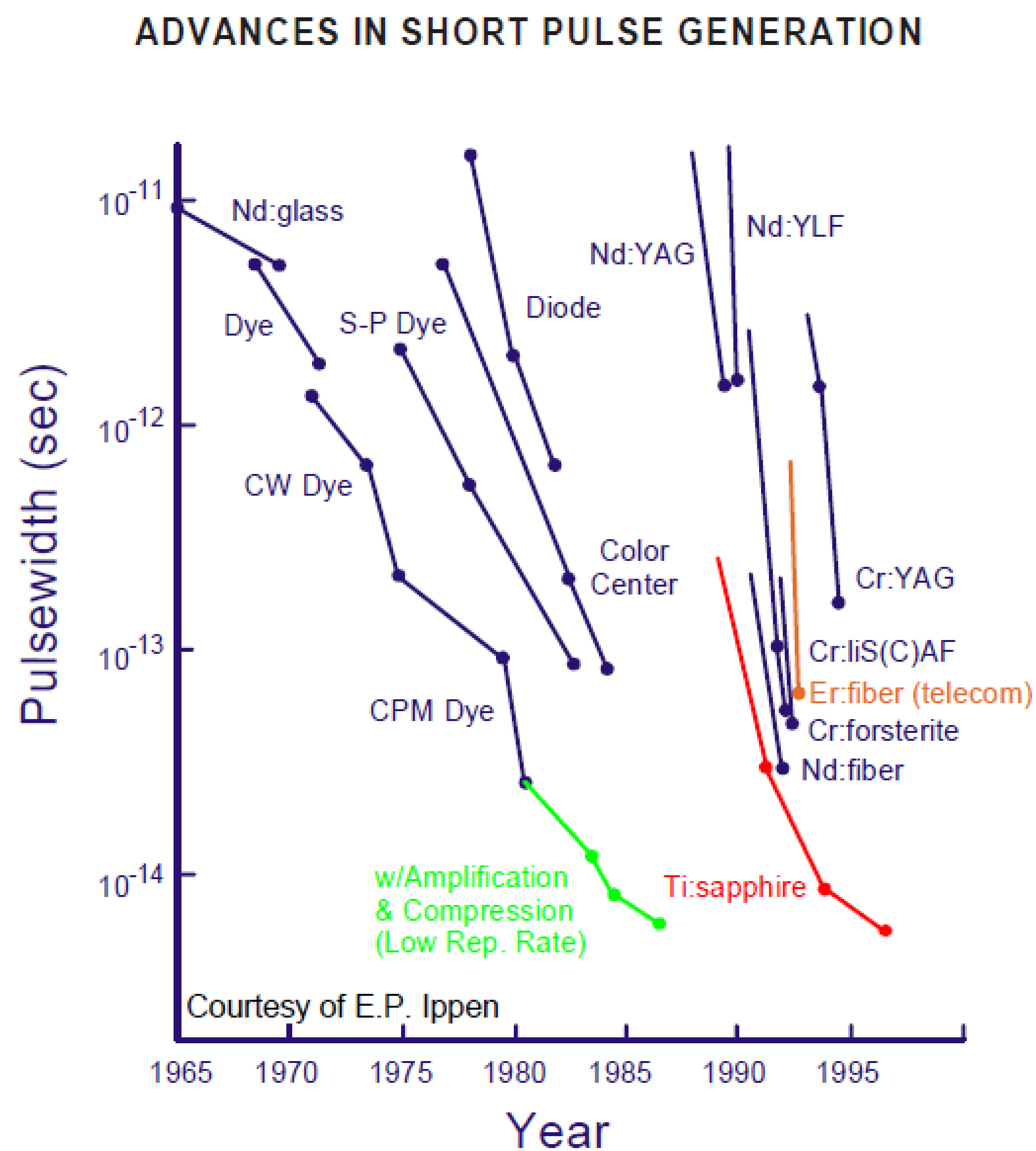


Figure 1





Historical Progress in Ultrashort Pulses

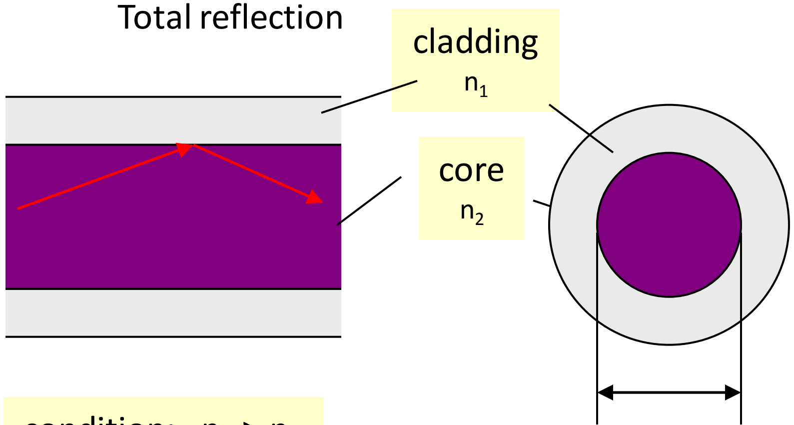


11. Fiber lasers

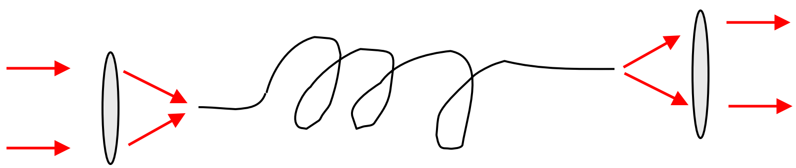
11.1 Introduction

Optical fiber

Total reflection



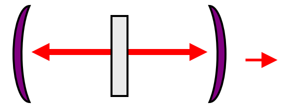
condition: $n_2 > n_1$



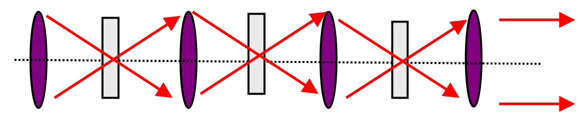
L … 10^3 km

Light can be guided (confined) in the core of optical fibers over great distances. This allows for large interaction lengths of light with an active medium that is doped into the fiber core.

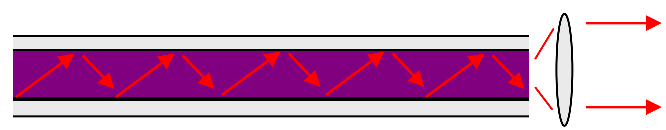
Realizing large gain



laser with resonator (many passes through the active medium)

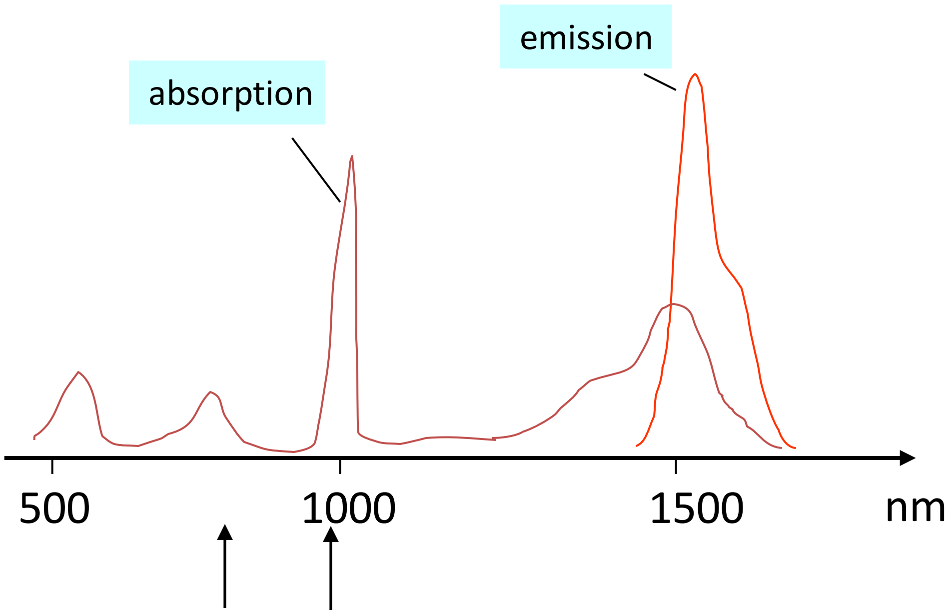


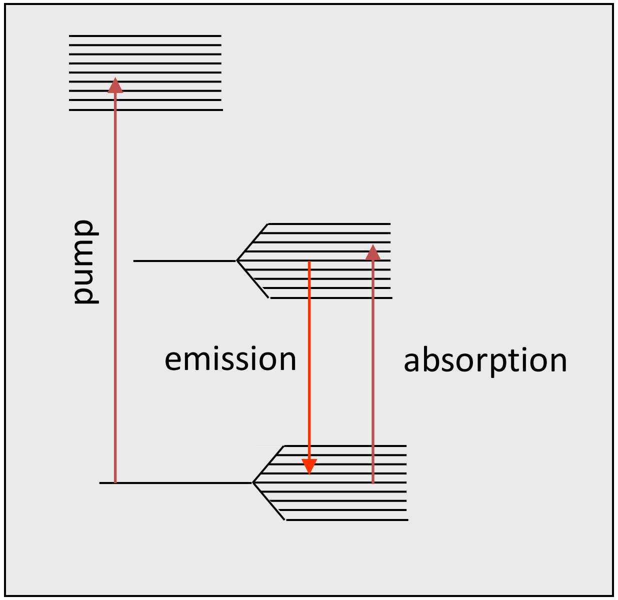
lens duct (unfolded resonator)



fiber laser

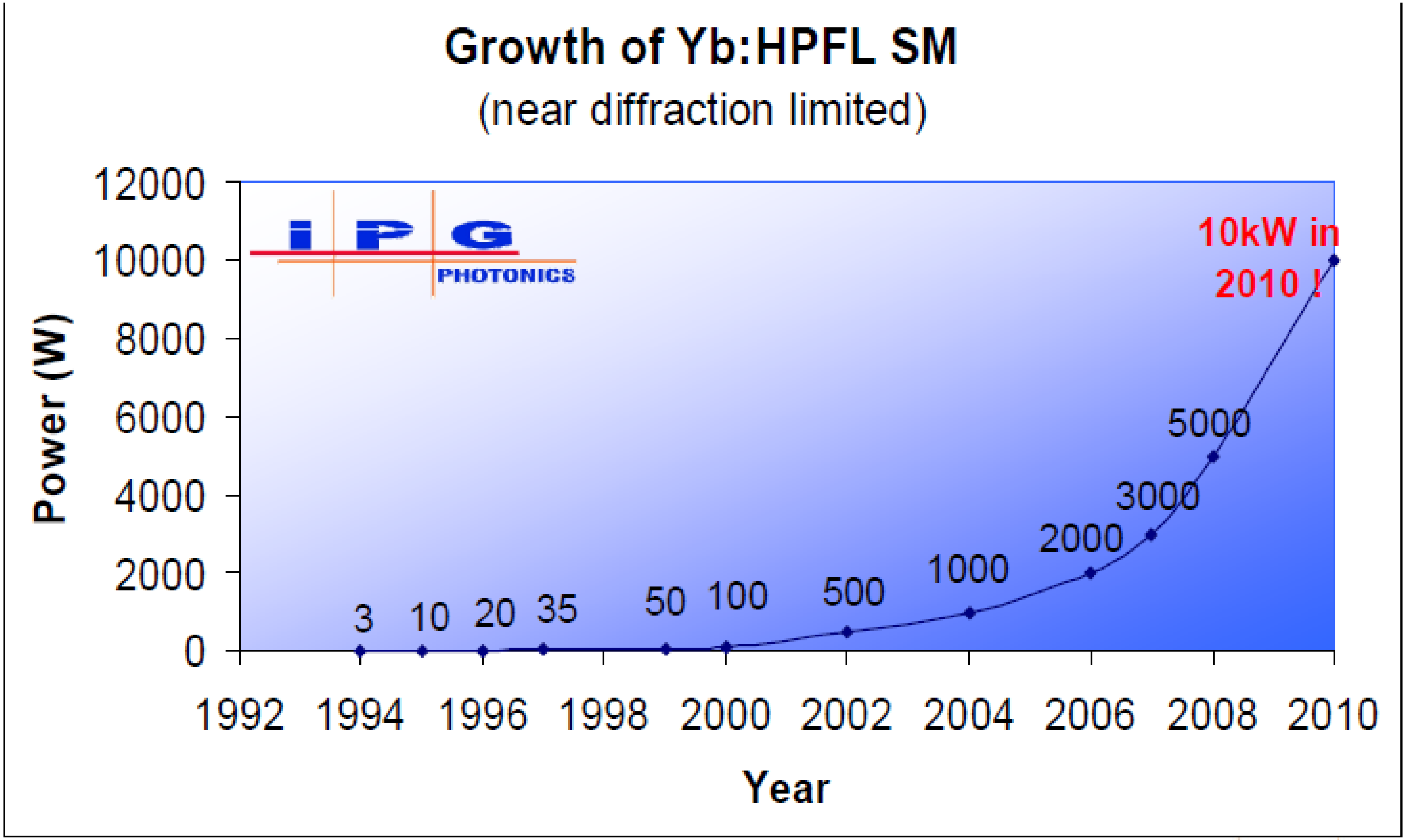
11.2 Example: erbium-doped glass fibers





pumping with diode lasers is possible

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


Growth of Yb:HPFL SM
(near diffraction limited)
IPG PHOTONICS
10kW in 2010 !
Power (W)
12000
10000
8000
6000
4000
2000
0
3
10
20
35
50
100
500
1000
2000
3000
5000
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year

IPG Fiber Lasers

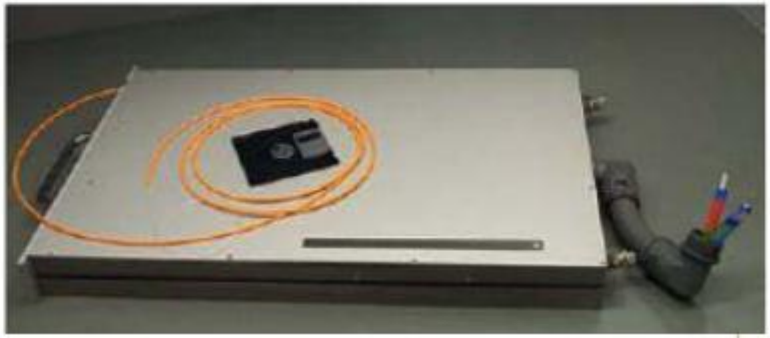
A single module can supply:

- 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

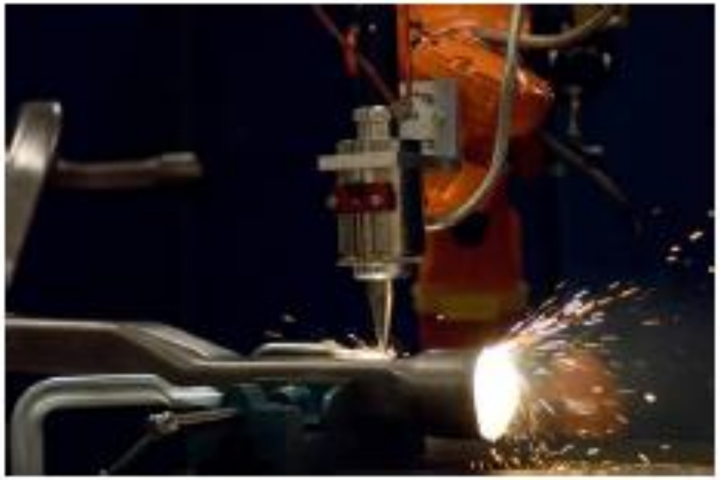
T x H x D = 60 x 33 x 4.7 cm

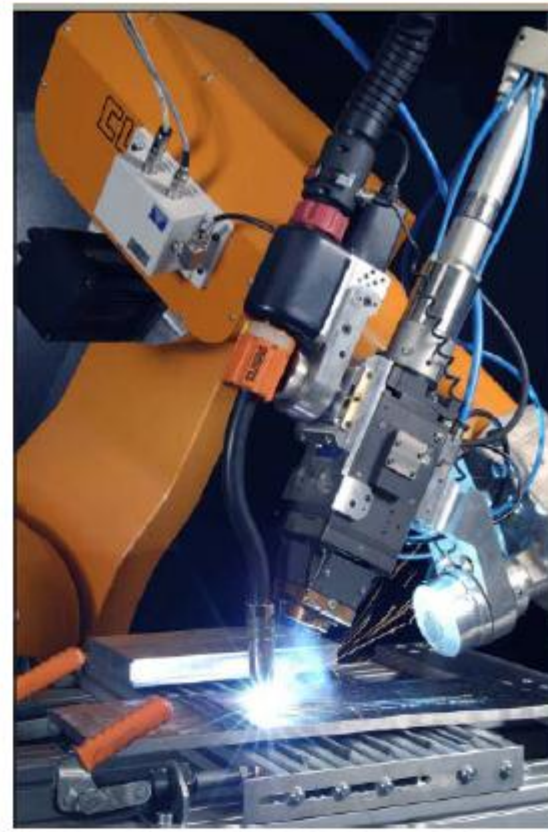
Efficiency (DC) > 35%

Building blocks (modules) for HPFLs



IPG PHOTONICS



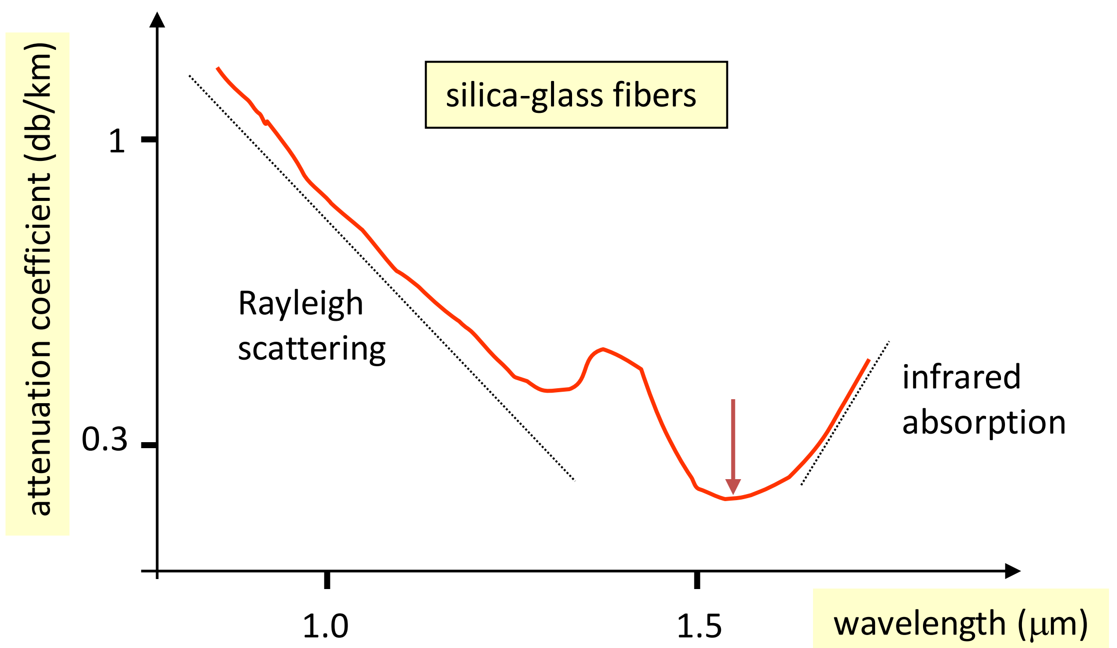


ALAW 2009

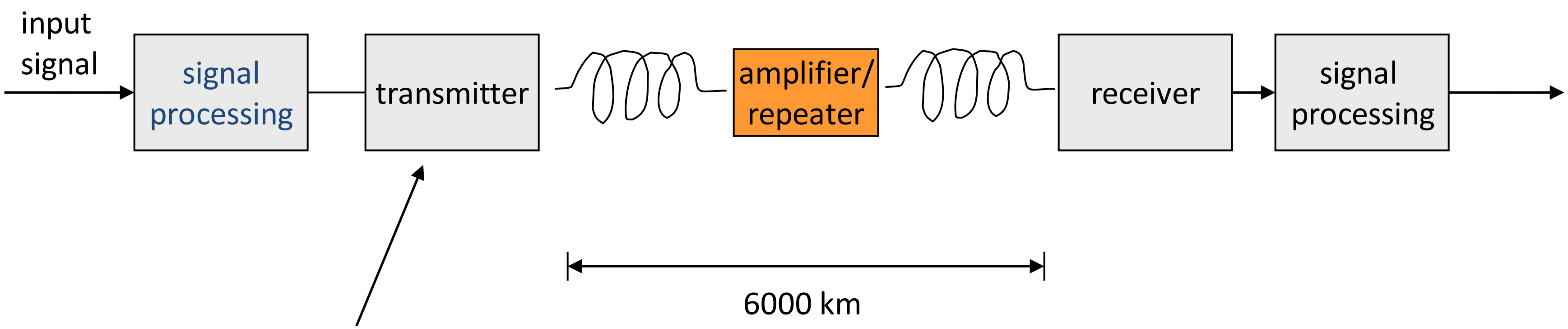
ALAW 2009

Why?

The carrier frequency of light (~ 10^{14} Hz) and subsequently the transmitted bandwidth is much larger than what can be achieved by electronics.



Fiber transmission line



InGaAsP
diode laser

- transatlantic US - UK
- 560 Mb/s per fiber pair
- 80000 simultaneous voice channels
- repeaters 100 km apart

12. Chemical Lasers

12.1 Introduction

- population inversion is produced by a chemical reaction

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

- 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

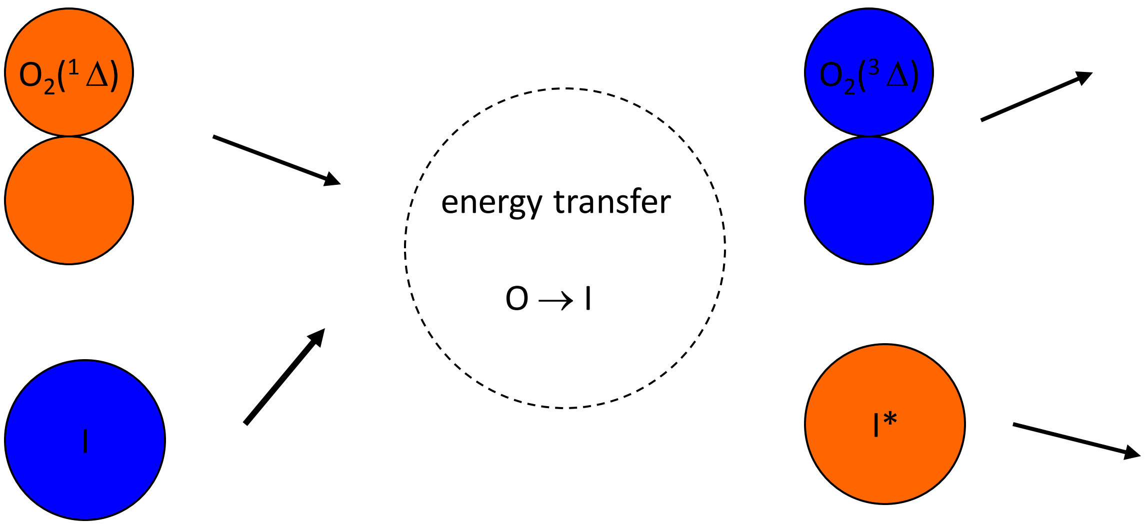
molecules in an excited vibrational state

atoms in an excited electronic state

12.2 The chemical oxygen-iodine laser

chemical reaction:

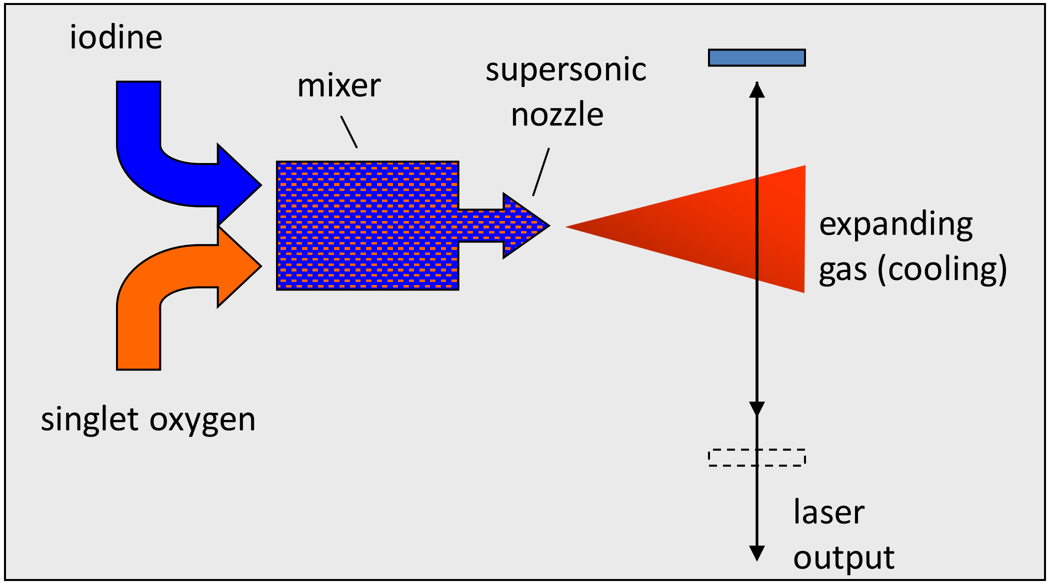
$O_2(^1\Delta) + I \leftrightarrow O_2(^3\Sigma) + I^*$



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