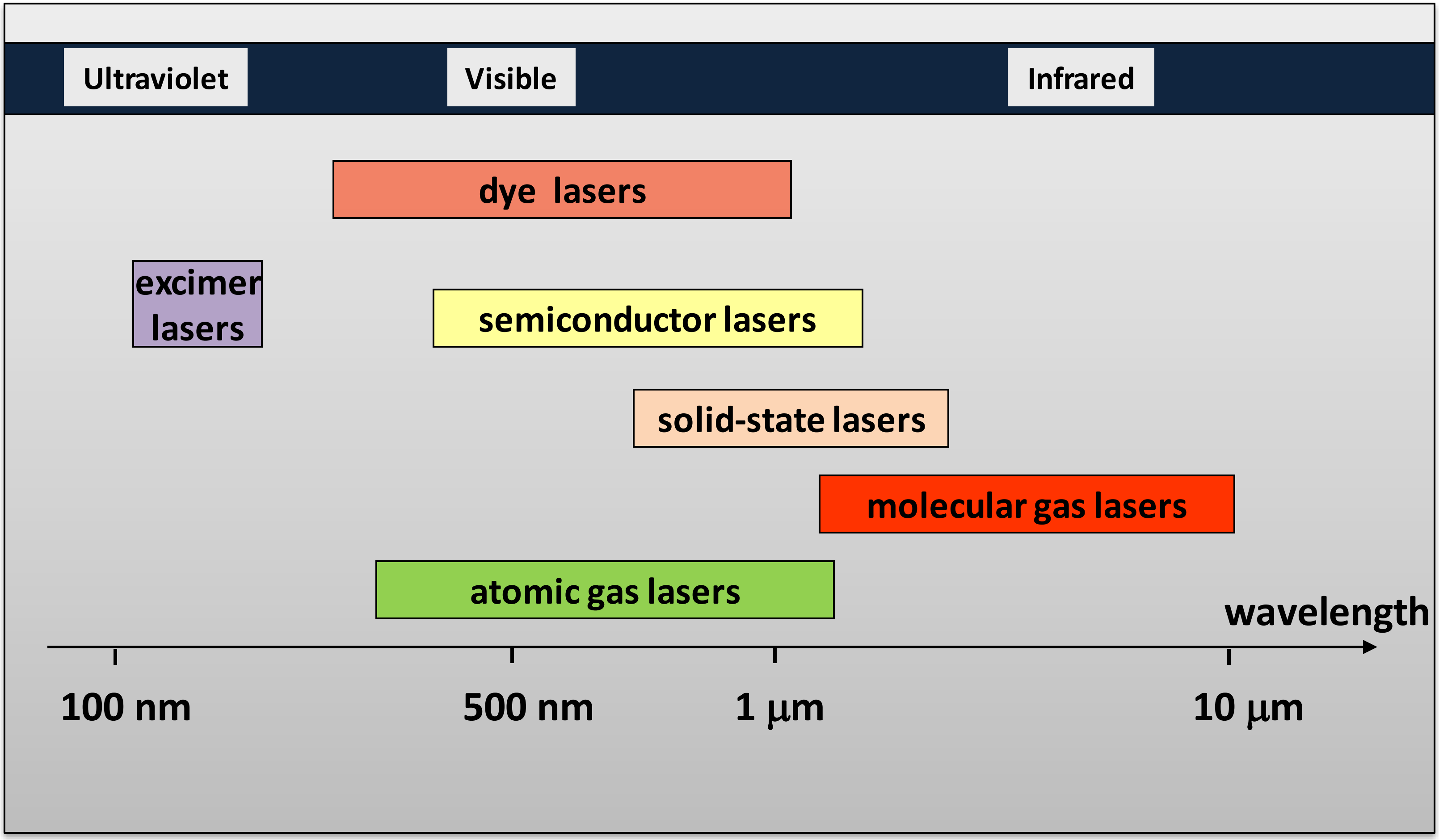
Optical Science & Engineering
University of New Mexico

Examples of Specific Laser Systems

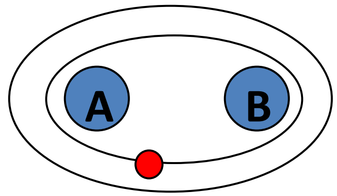
- Gas Lasers
  - CO_2 200+ kW
- Solid-State Lasers
  - Nd:YAG (15 kW)
- Fiber Lasers
  - Yb^{3+} (5+ kW)
- Dye Lasers
- Chemical Lasers
  - COIL (7+kW), MIRACL (>1 MW !!)
- Semiconductor Lasers

Active media and spectral ranges



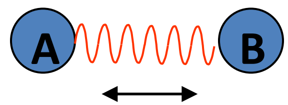
emission

electronic transitions



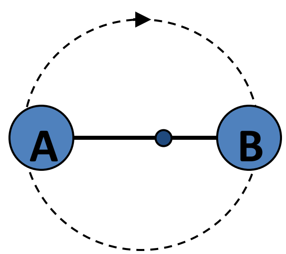
VIS, UV

vibrational transitions

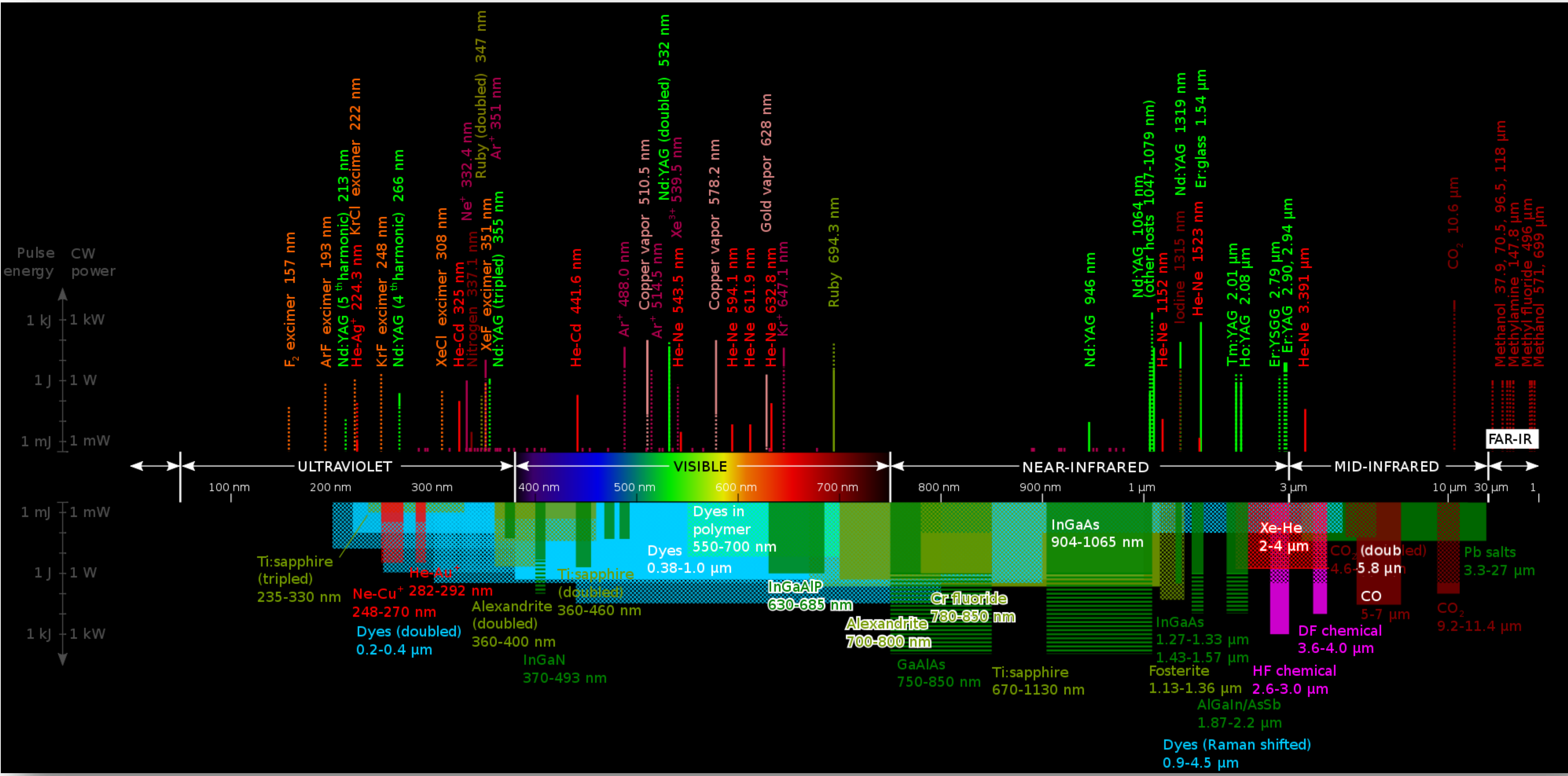


NIR, IR

rotational transitions



FIR



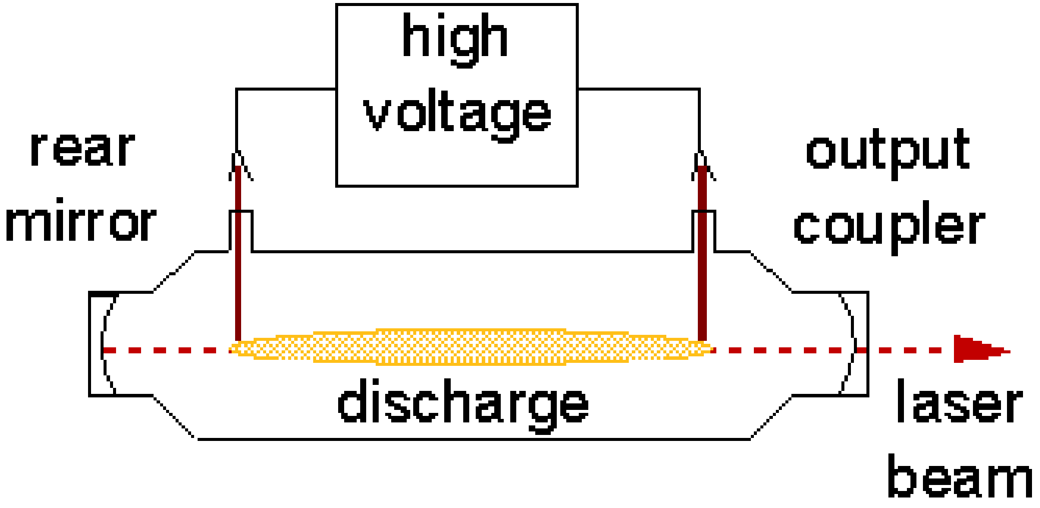
Pulse energy
CW power
1 kJ
1 kW
1 J
1 W
1 mJ
1 mW
F2 excimer 157 nm
ArF excimer 193 nm
Nd:YAG (5 th harmonic) 213 nm
He-Ag+ 224.3 nm
KrCl excimer 222 nm
KrF excimer 248 nm
Nd:YAG (4 th harmonic) 266 nm
XeCl excimer 308 nm
He-Cd 325 nm
Nitrogen 337.1 nm
Ne+ 332.4 nm
Ruby (doubled) 347 nm
XeF excimer 351 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 nm
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
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
1
Ti:sapphire (tripled) 235-330 nm
He-Au+
Ne-Cu+ 282-292 nm
248-270 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%
Fiber Lasers	<30%
GaAlAs (diode laser)	< 40%
HeNe	< 0.1%
Nd:YAG	< 10%

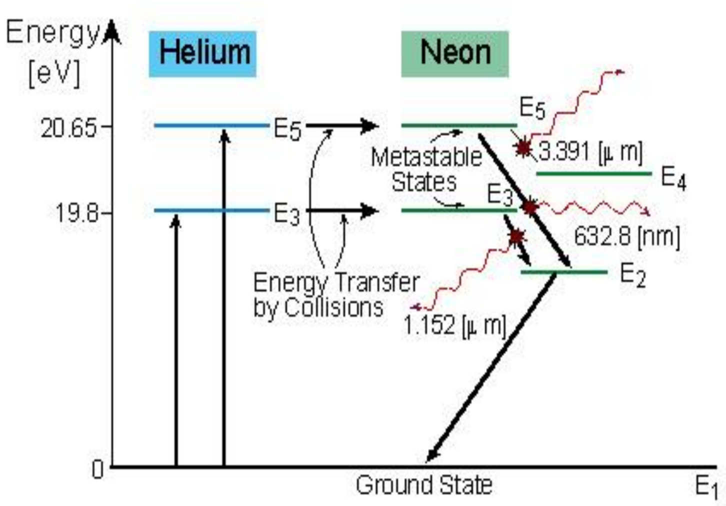
Gas Lasers

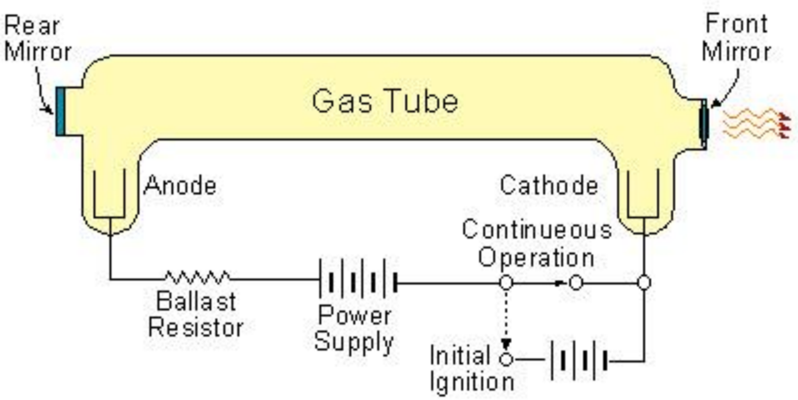


The excitation mechanism in most gas lasers is via *electric discharge*

The first Gas Laser: He-Ne

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





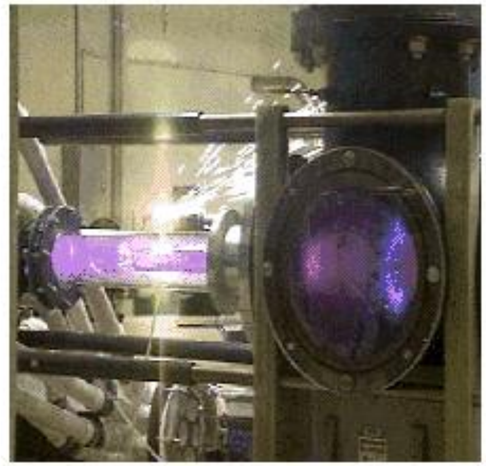
- The second working LASER system to be demonstrated.
- The first gas LASER to be produced.
- The first LASER to produce a continuous output beam
- The active laser medium is a gaseous mixture of He & Ne atoms, in a roughly 10:1 proportion
- The gas is enclosed in a cylindrical quartz DISCHARGE tube

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

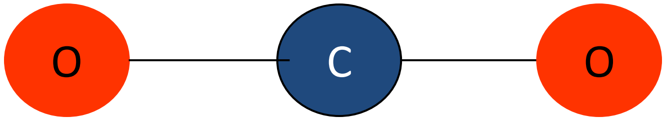


Applications (*pealing peanuts to star wars*)

- 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.

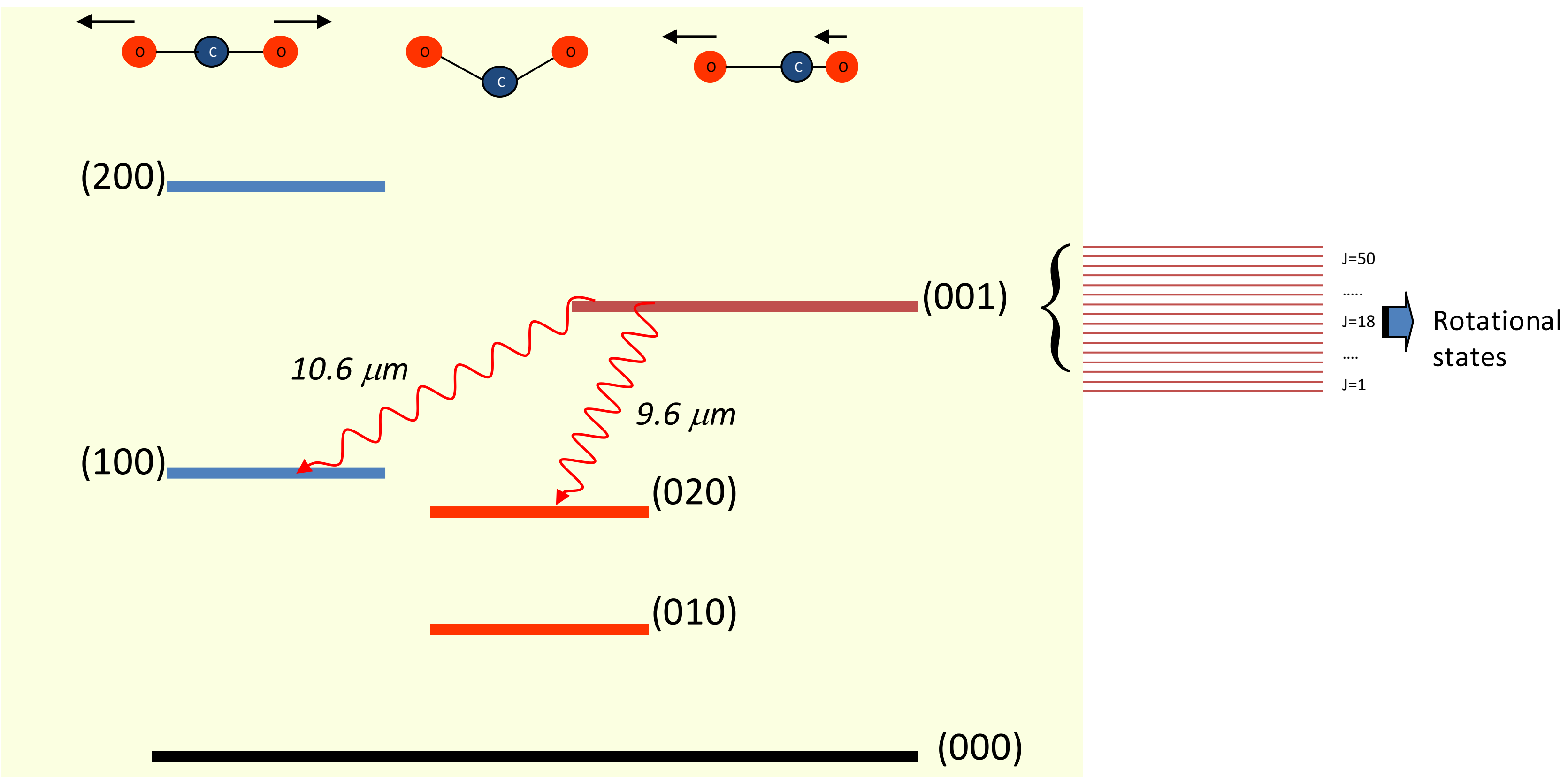


Modes of vibrations:

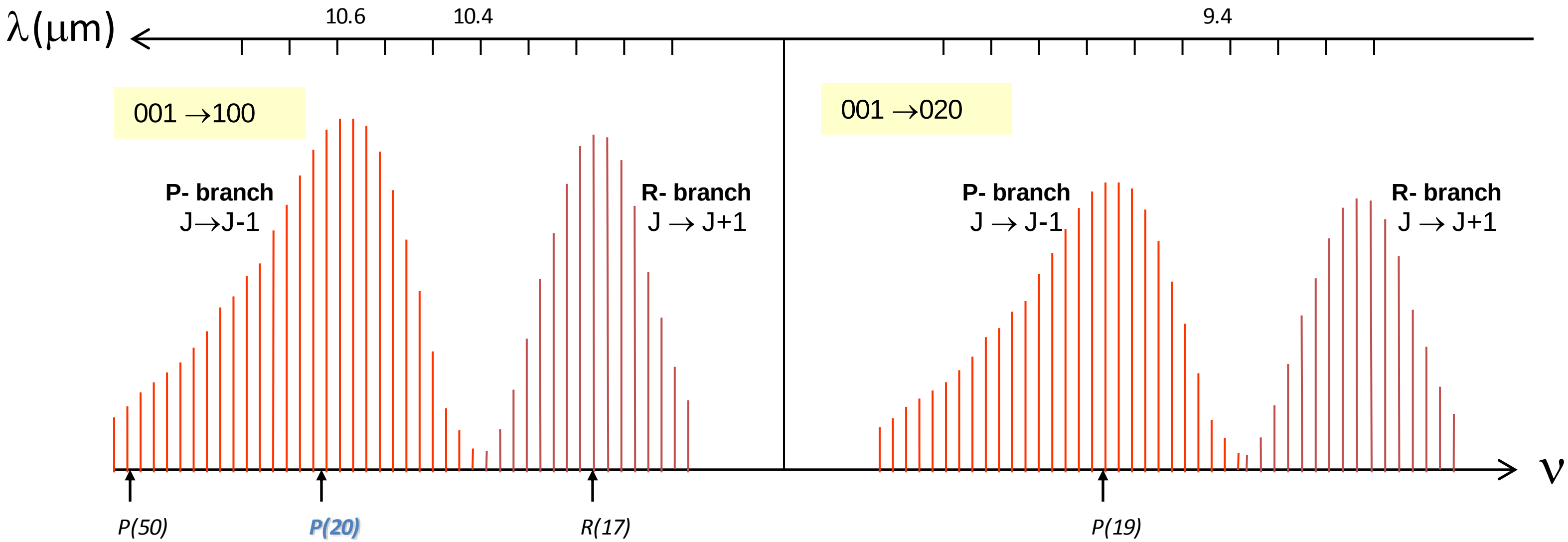
- Symmetric stretch
- Asymmetric stretch
- Bending mode

Simple Harmonic Oscillator (Quantum Mechanics):

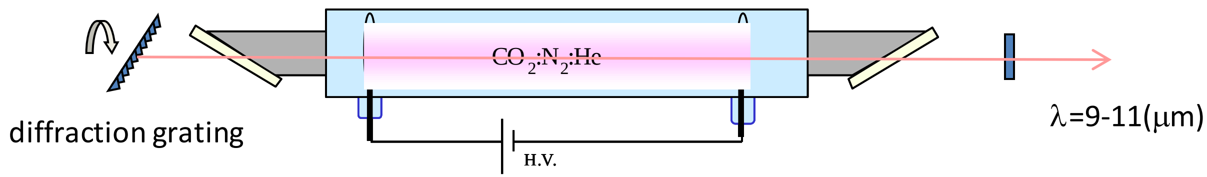
$$E(n_1, n_2, n_3) = h\nu_1(n_1 + 1/2) + h\nu_2(n_2 + 1/2) + h\nu_3(n_3 + 1/2)$$



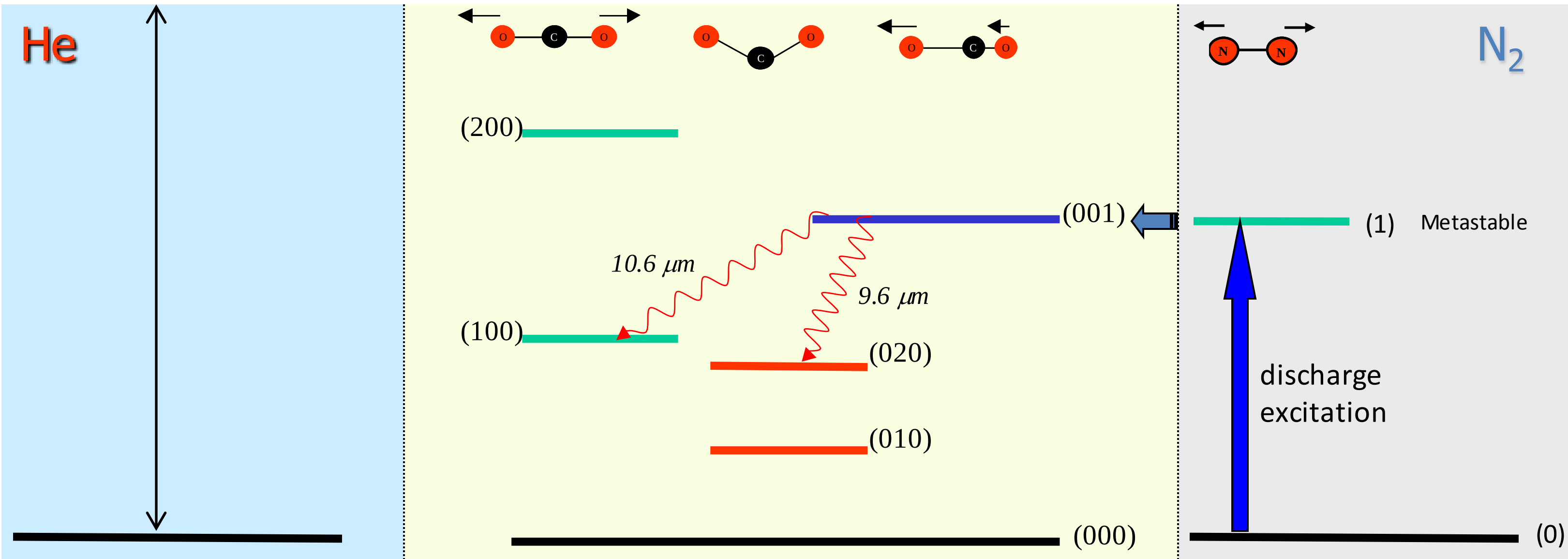
CO_2 Laser Transitions



Tuning:



Effect of Gas Mixtures: CO_2+N_2+He



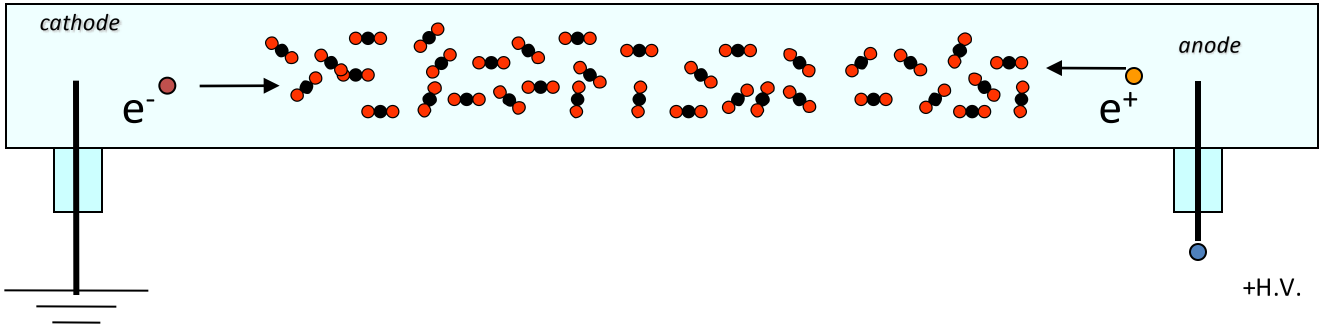
- Nitrogen helps populating the upper laser level in a discharge
- Helium helps to depopulate the lower laser level by collisions

Other possible additions to the gas mixture: CO, H_2

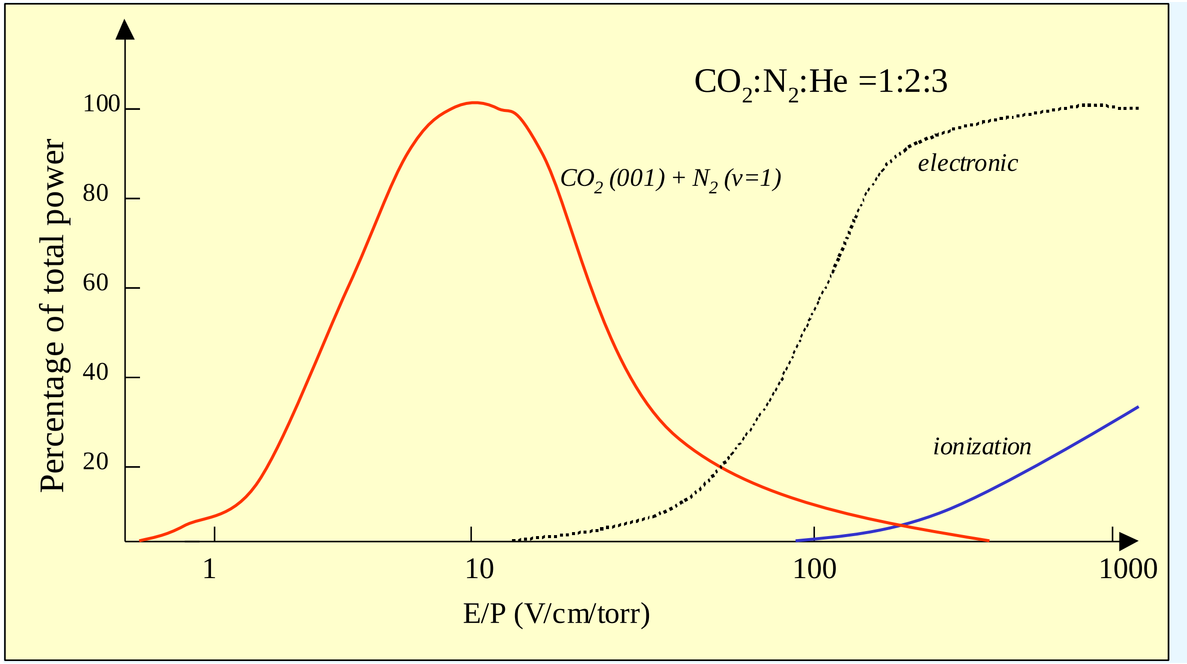
Typical Co_2:N_2:He Gas Ratios Recommended by Laser Manufacturers

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:

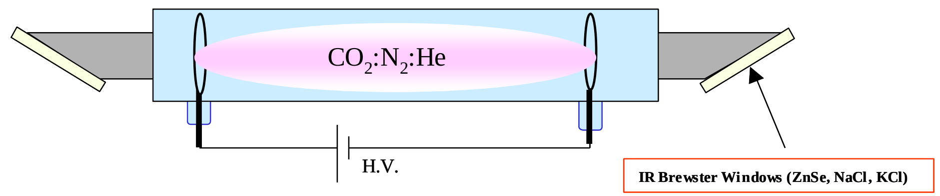
L=1 meter and P=25 torr

Need V=25 kV for optimum operation

11.4 Specific Types of CO_2 Lasers

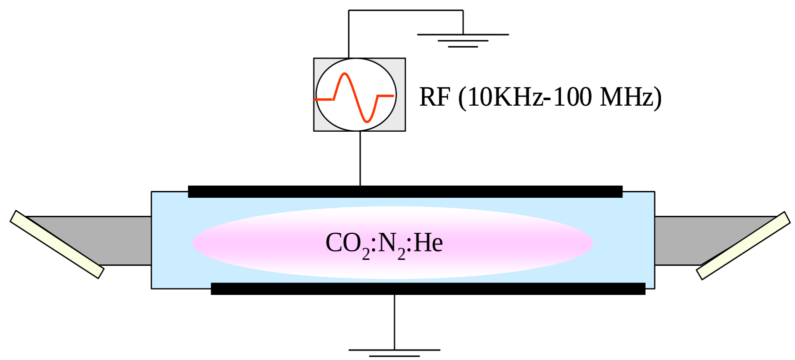
High Power CW Operation

❑ 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

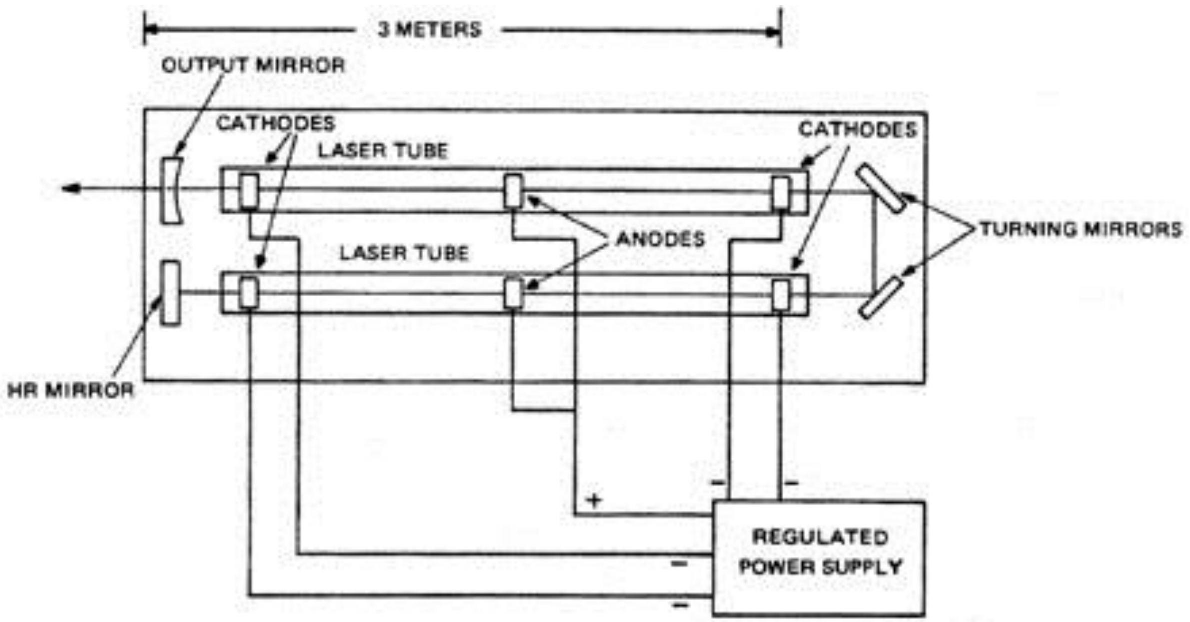
❑ RF-Discharge



- 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

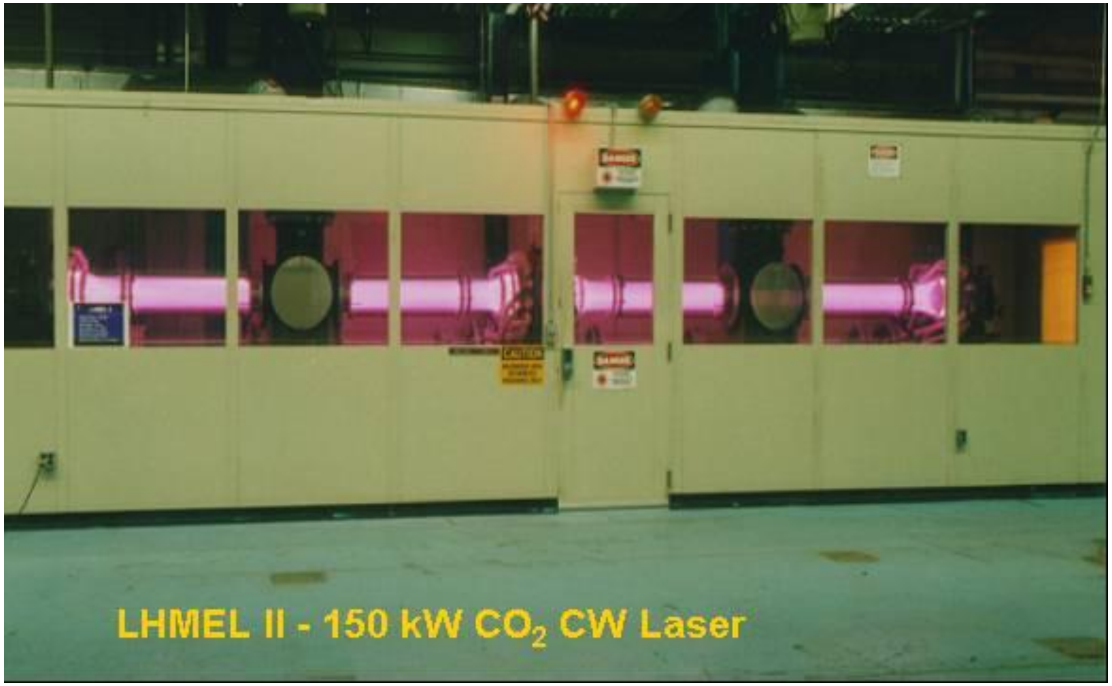
Example: A 250 W CW CO_2 Laser

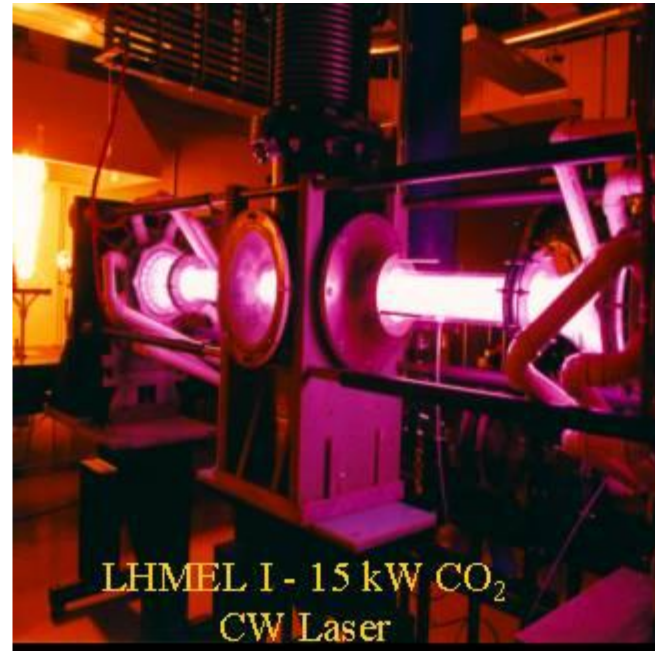


Operating Parameters of Commercial Class I CO_2 Lasers.

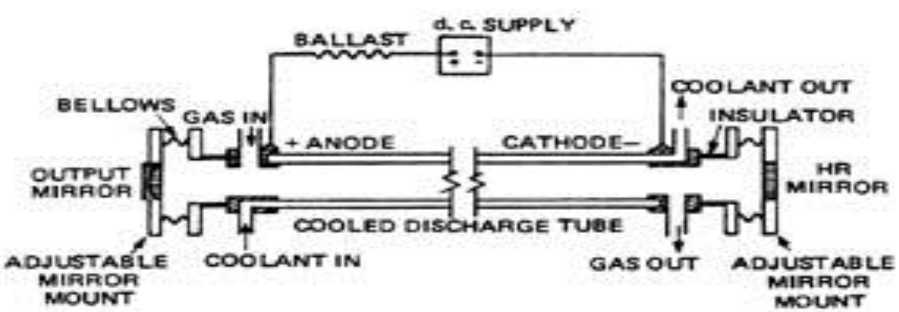
Active Length meters	Output Power watts	Gas Mixture CO_2:N_2:He	Gas Flow Rate liters/min	Power/ Length W/m	Water Flow Rate liters/min
1	50	1:1.5:9.3	1.15	50	2
2	100	1:1.5:9.3	1.15	50	2
5	275	2:1.35:9.3	4.01	55	10
6	375	1:8:23	4.26	62.5	10
9	525	1:6.7:30	4.23	58.3	10
18	1000	1:2.35:17	14.35	55.6	15

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





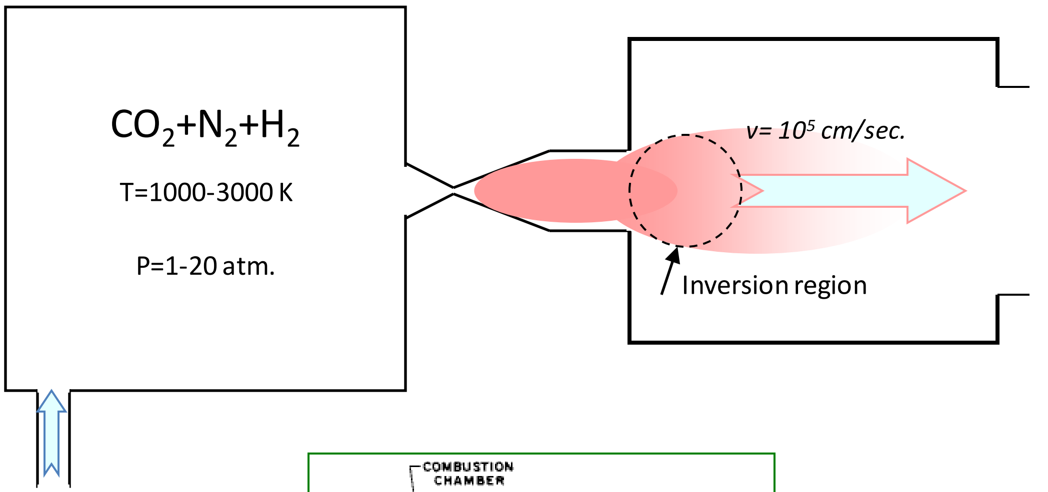
Electric Discharge Coaxial Laser (EDCL)

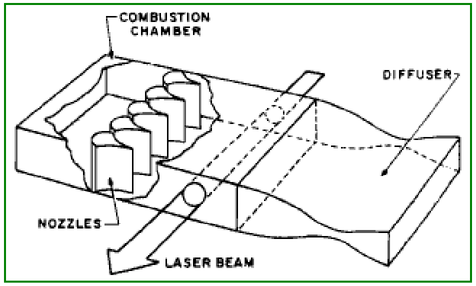


❑ Gas-Dynamic Lasers

Basov & Oraevskii (1963)

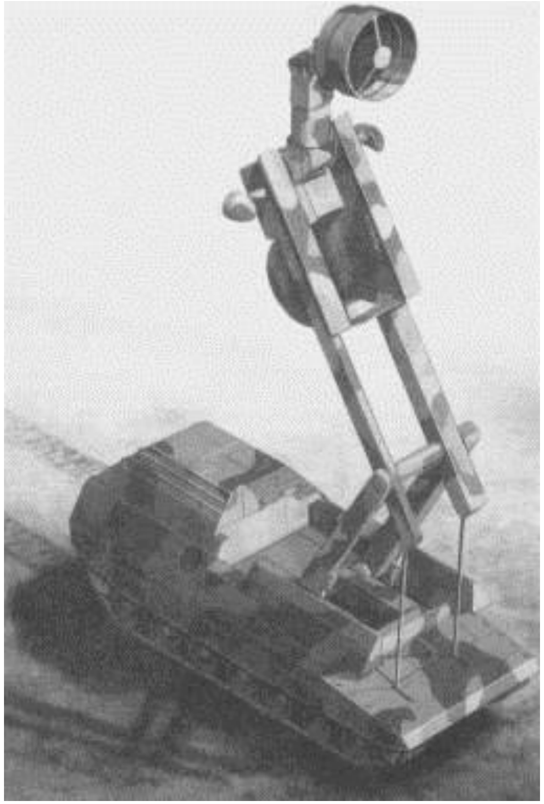
Principle: *Population inversion by rapid expansion (supersonic flow) of s super-heated gas*





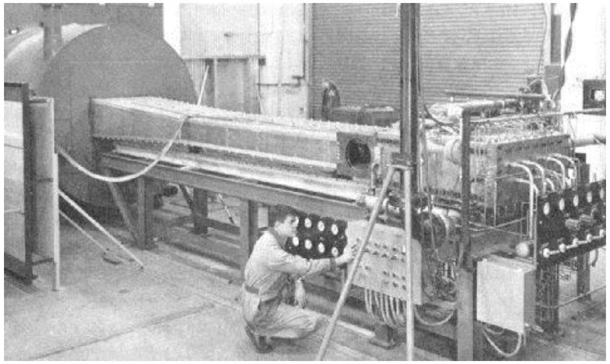
•cw powers up to 1 MW have been obtained from gas-dynamic CO_2 lasers !!

Gas-Dynamic Lasers

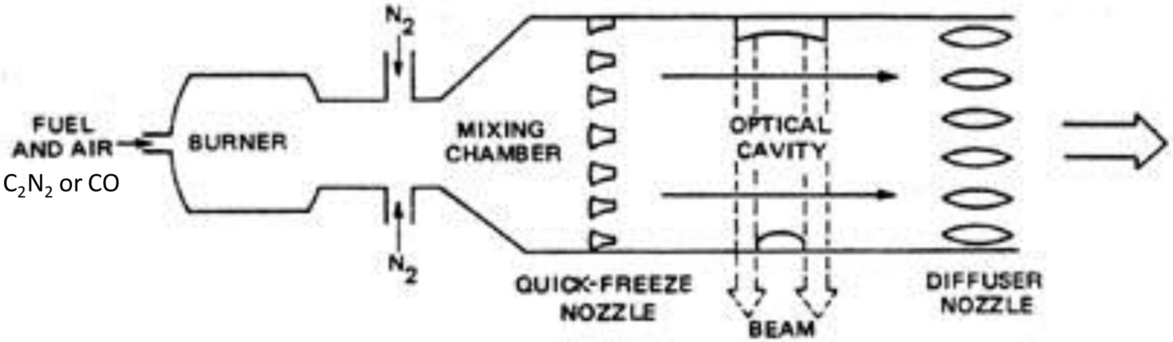


HELEX

High Energy Laser Experimental
Germany, 1970's

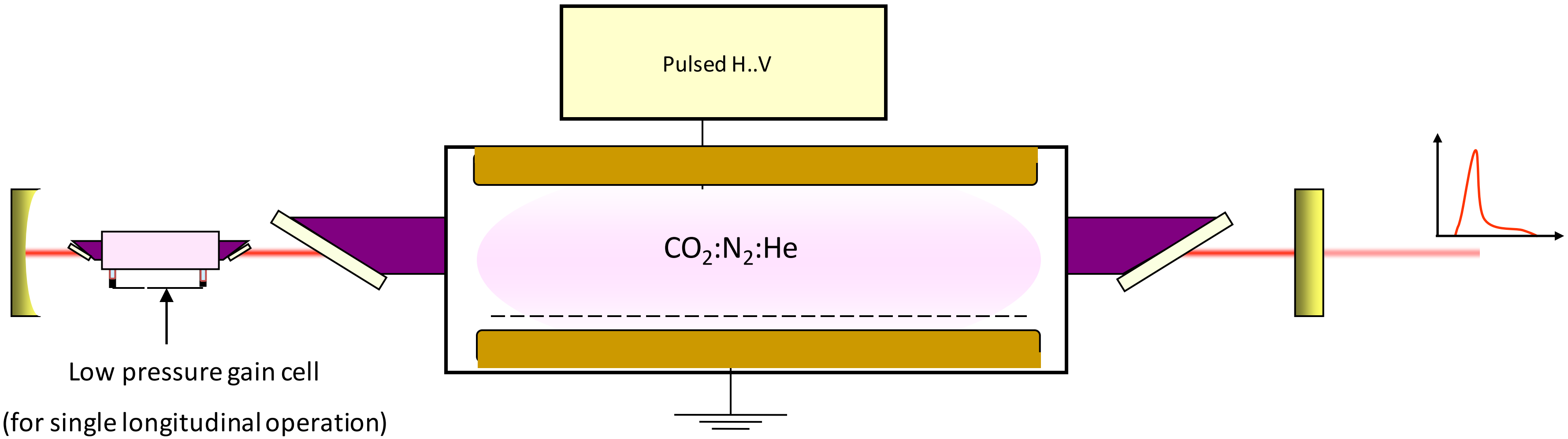


Large scale 135 Kilowatt gasdynamic laser at Avco Everett Research Lab.



•Pulsed CO_2 Lasers

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



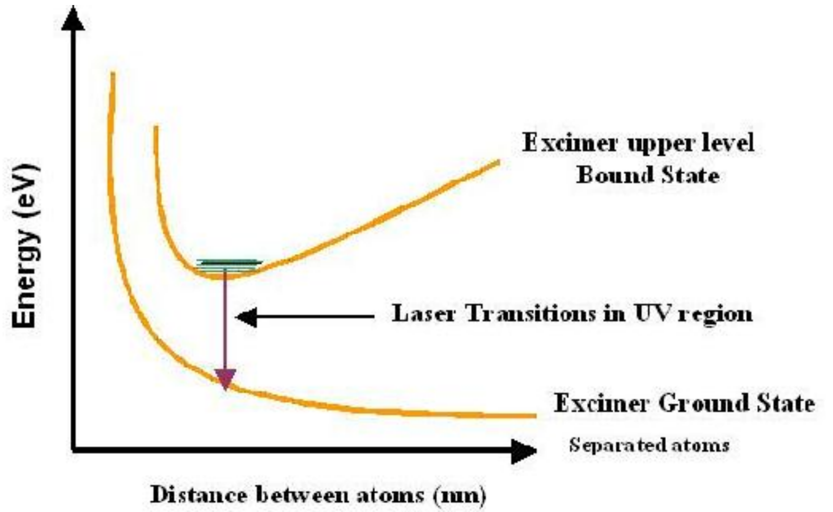
- Flowing or sealed systems
- Pulsewidths from 50 ns to 300 ns
- Repetition rates: 1Hz. to 1 kHz.
- Pulse energy: 50 mJ to 10 J (amplified)

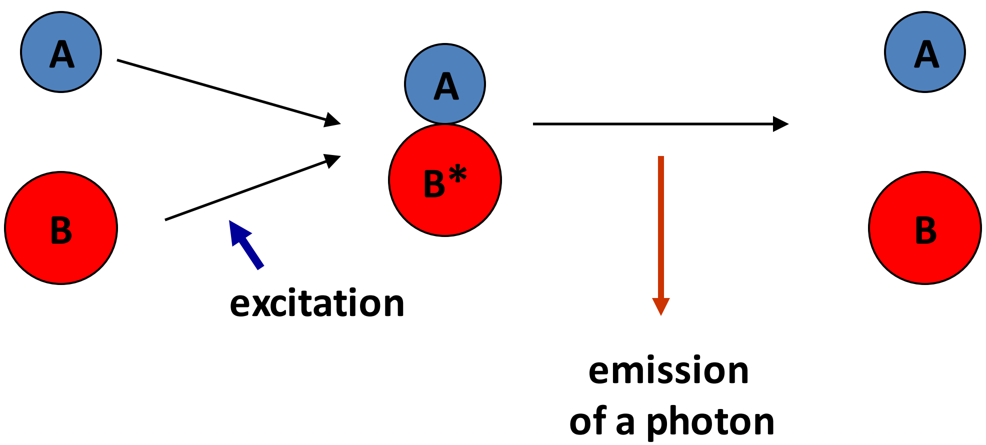
Excimer Lasers: applications in lithography and eye surgery

With phenomenal advances made in equipment technology in the last two decades, and today microelectronic devices fabricated using excimer laser lithography totaling **$400 billion** in annual production, it is the semiconductor industry view that excimer laser lithography has been a crucial factor in the continued advance of Moore's law, enabling minimum features sizes in chip manufacturing to shrink from 0.5 micrometer in 1990 to 22 nanometers in 2012. This trend is expected to continue into this decade for even denser chips, with minimum features approaching 10 nanometers. From an even broader scientific and technological perspective, since the invention of the laser in 1960, the development of excimer laser lithography has been highlighted as one of the major milestones in the 50-year history of the laser.

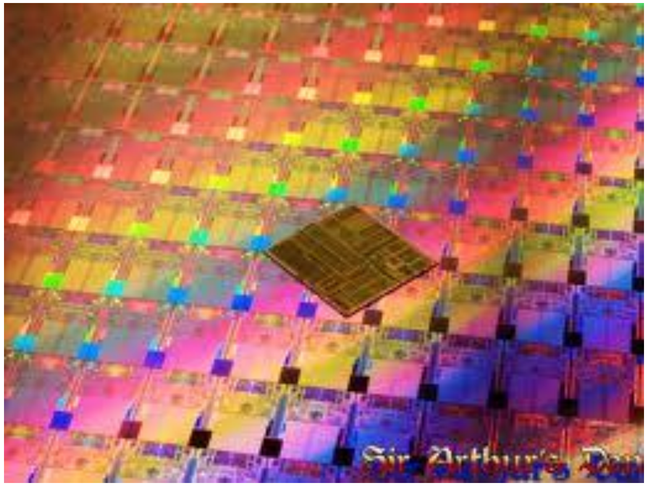
molecules exist only in the excited state

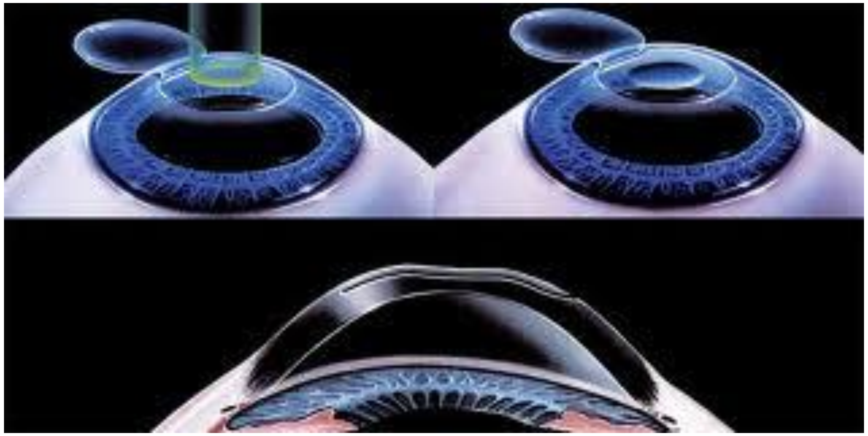
XeCl 308 nm
KrF 248 nm
ArF 193 nm
F_2 156 nm






GIGAPHOTON
GT62A
DANGER

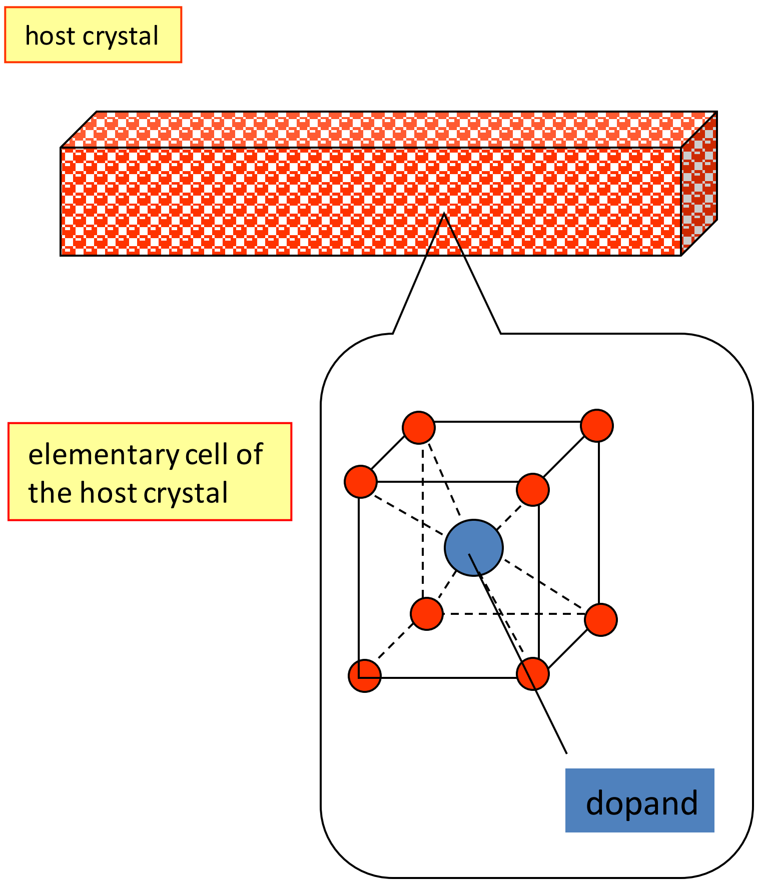

Sir Arthur's Den



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)

1	2											3	4	5	6	7	0
							H										He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Transition metals

Optical Science & Engineering
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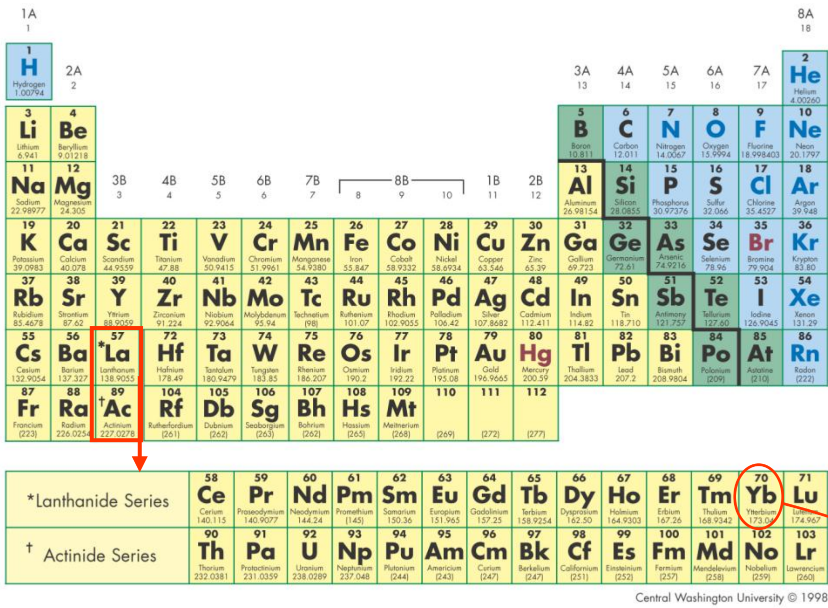
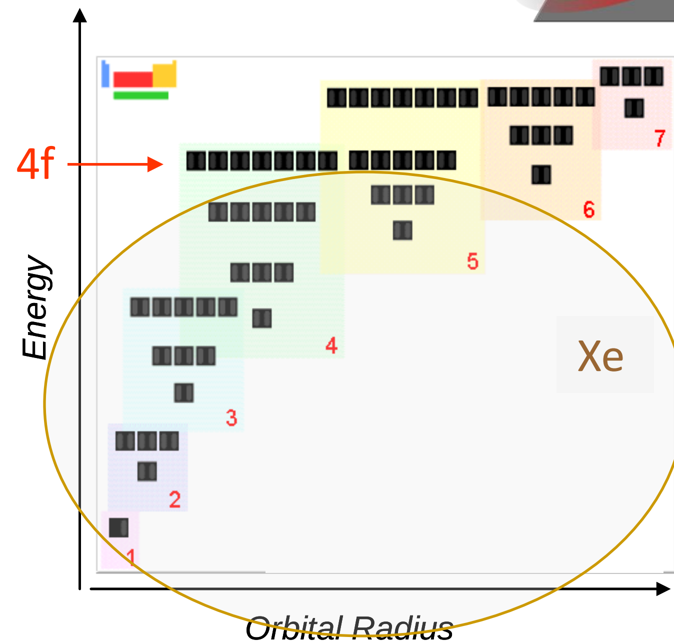
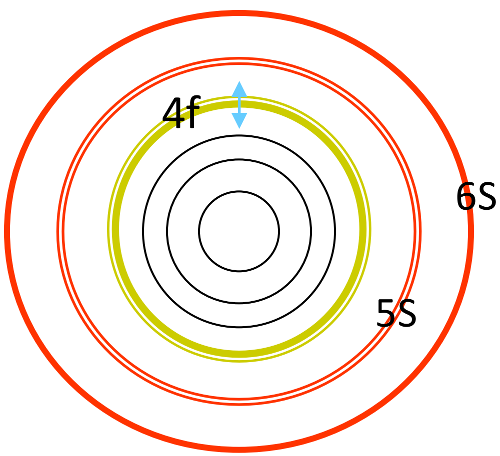
The 4f-4f transitions in Rare-Earths Ions:

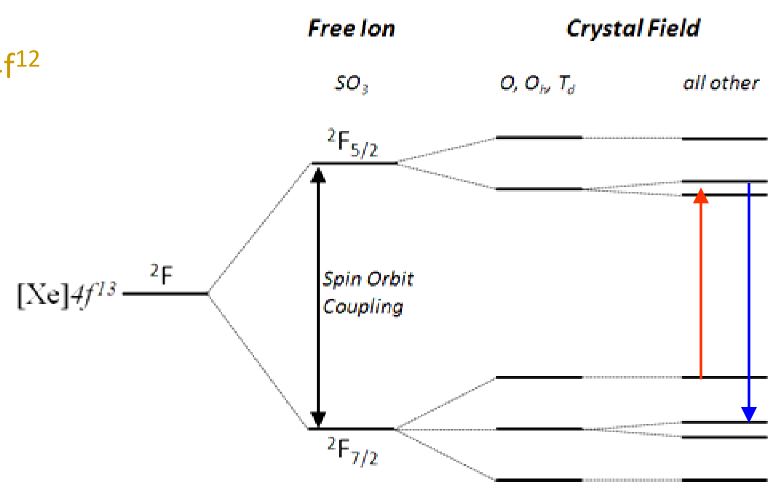




Yb ➡ $(Xe)4f^{13}6s^{2}$

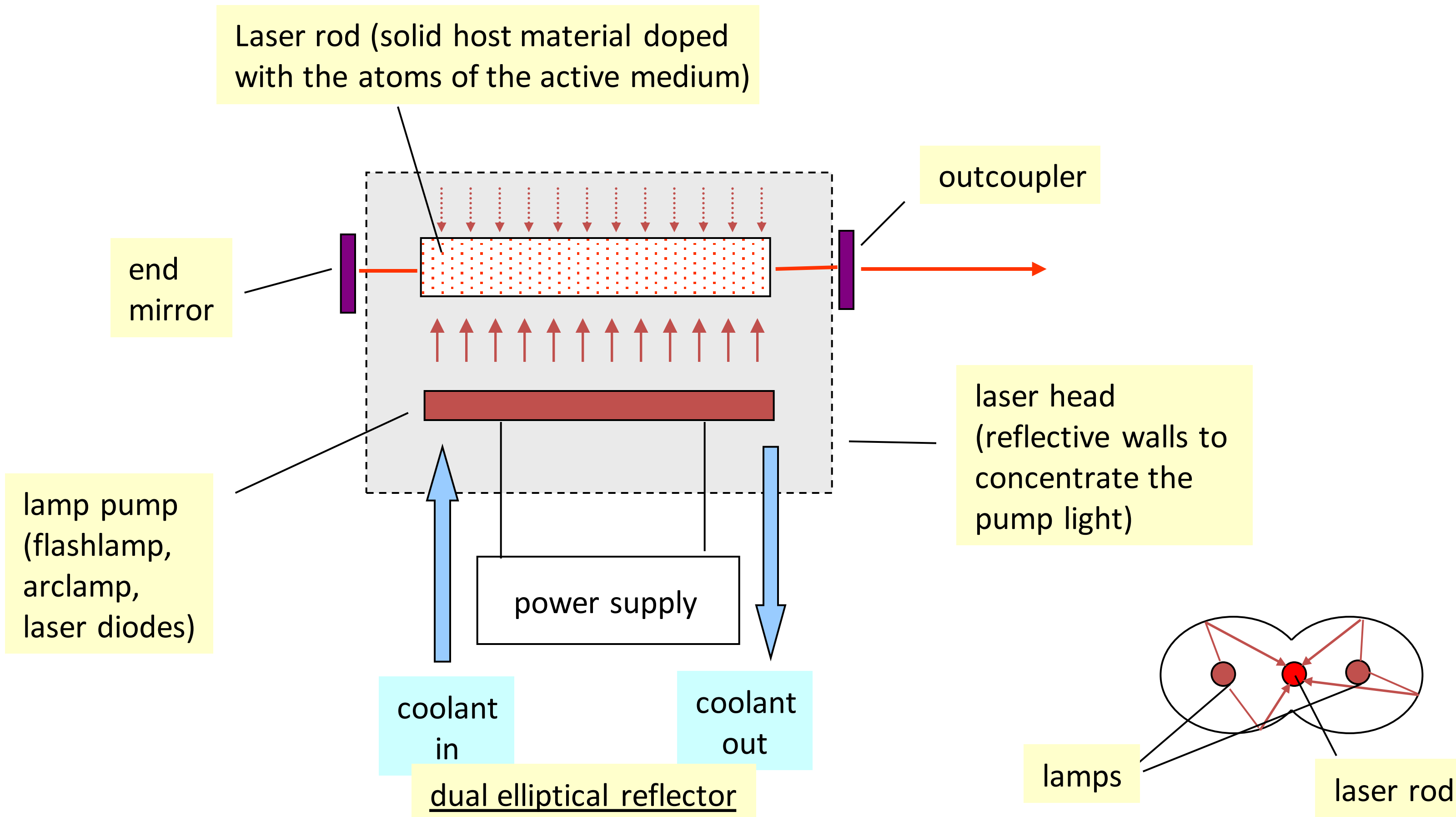
$Yb^{3+} = (Xe)4f^{12}$



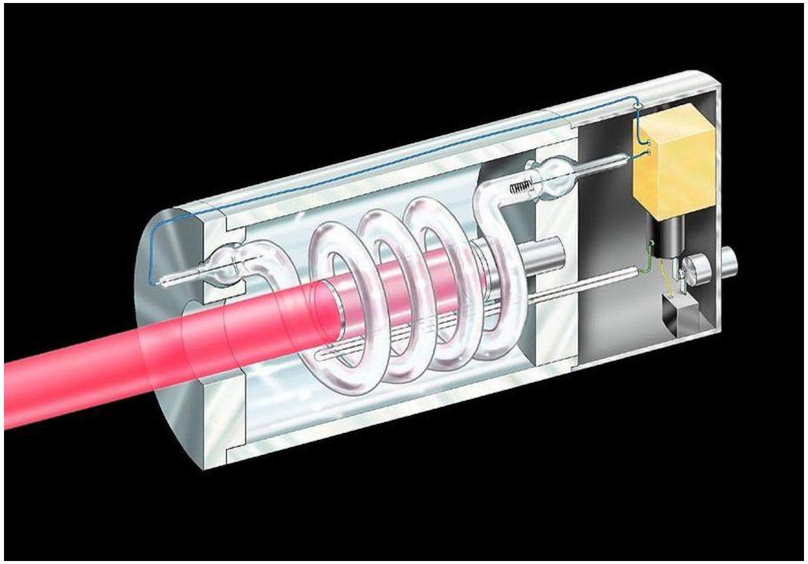


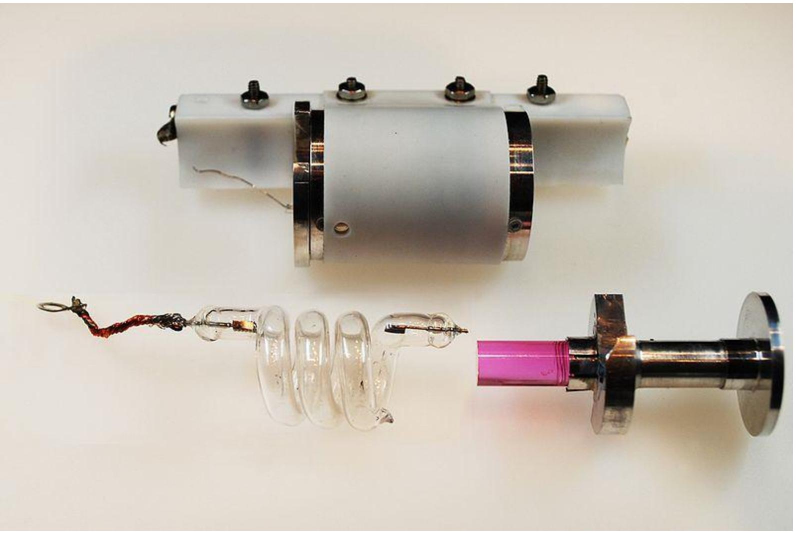
		He-Ne	Nd:YAG	$Ti:Al_2O_3$
	λ	633 nm	1064 nm	700 - 1000 nm
SSL: much smaller cross sections	σ	$3x10^{-13}$ cm^{-2}	4×10^{-19} cm^{-2}	4×10^{-19} cm^{-2}
SSL: much longer lifetimes	τ_2 / τ_1	60 ns/10 ns	250 µs/~30 ns	3.2 µs/fast
SSL: much higher saturation intens.	I_{sat}	2 W/cm^2	2 kW/cm^2	200 kW/cm^2
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	$\Delta\omega$	$2\pi \times 1.5$ GHz	$2\pi \times 200$ GHz	$2\pi \times 100$ 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



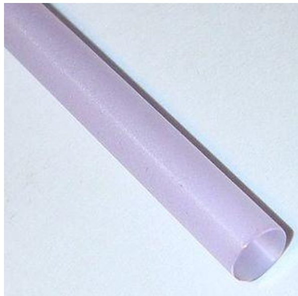
Maiman's Ruby Laser



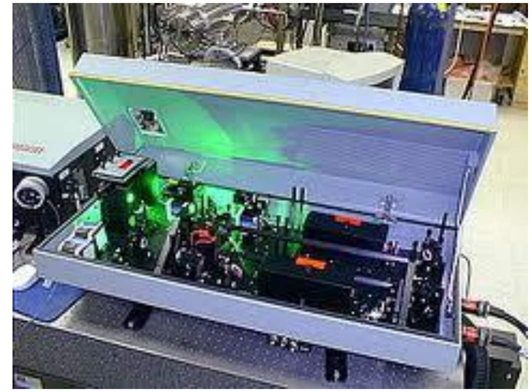


Nd:YAG Laser

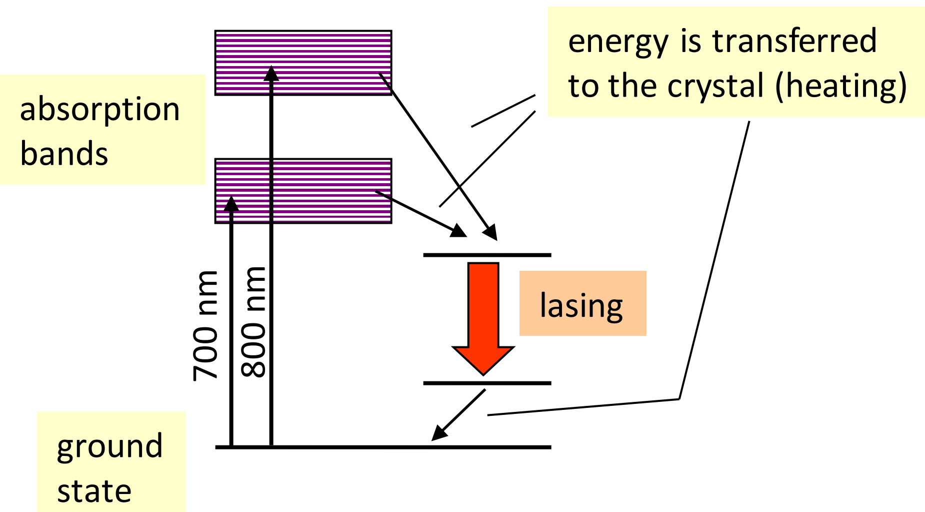
Nd:YVO_4

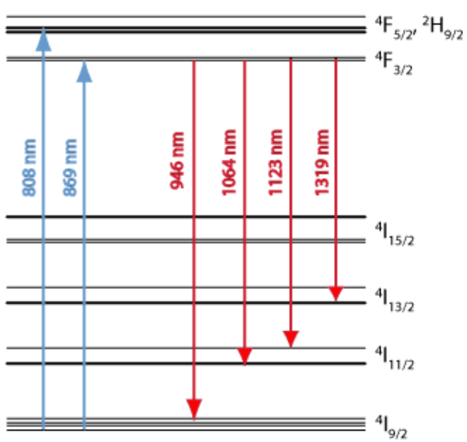


The most common solid-state laser is based on Nd atoms as dopands.



Energy diagram of Nd:

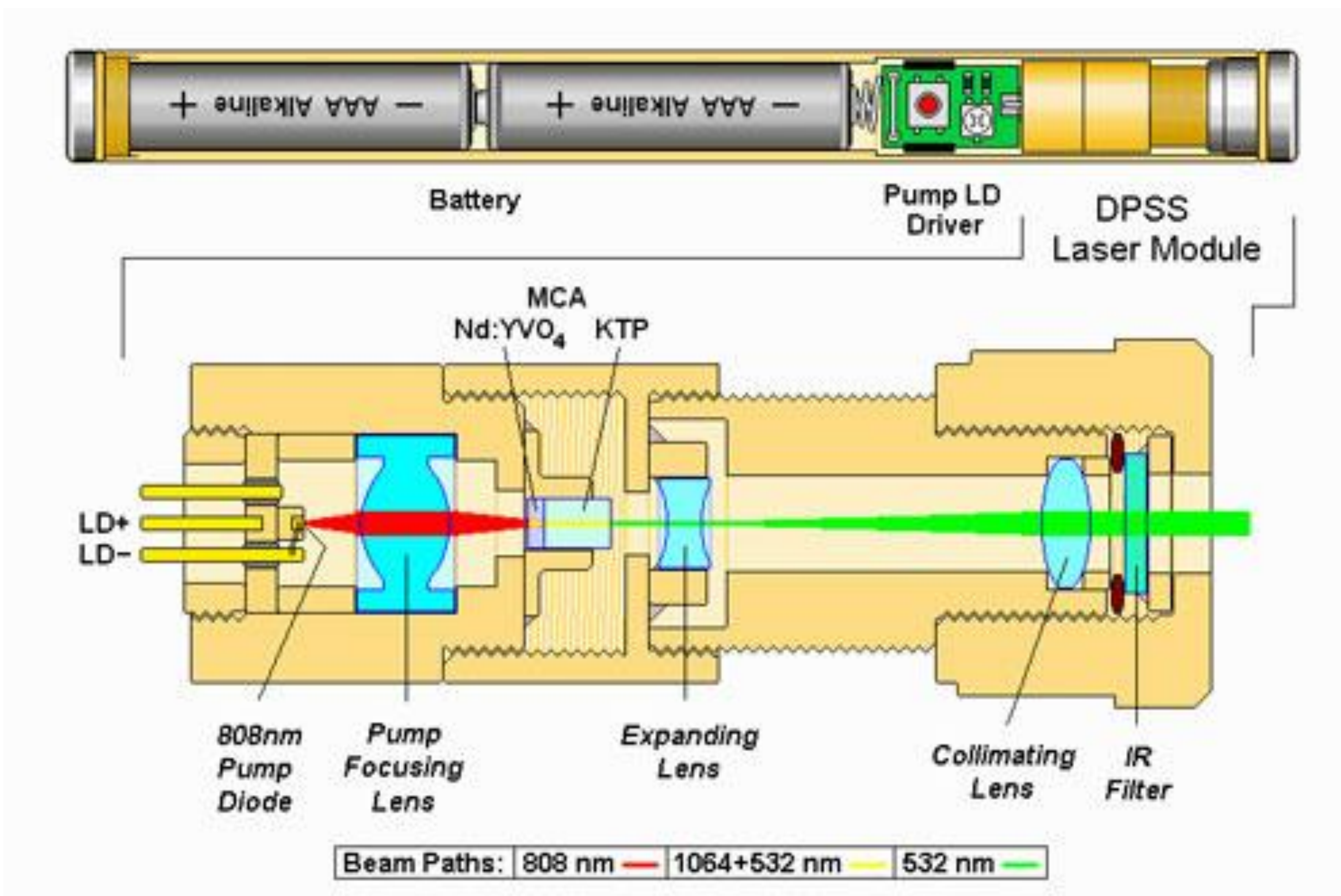




Output (Nd:YAG)

cw: $\leq$ 1000 W
pulsed: pulse energy $\leq$ 1 Joule
Q-switched - 10 ns pulse duration
modelocked – 10-100 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!!

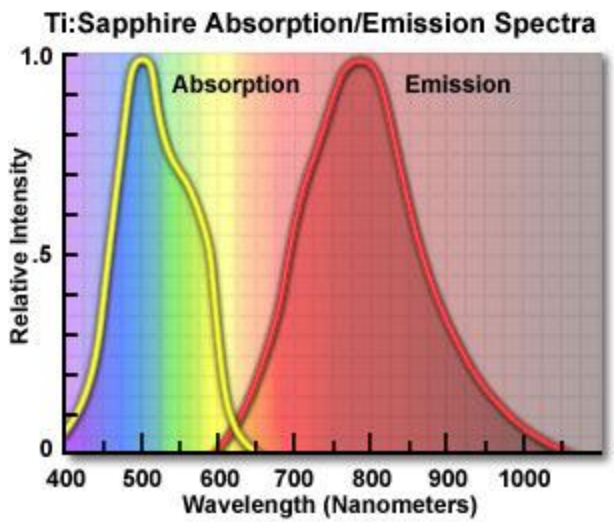
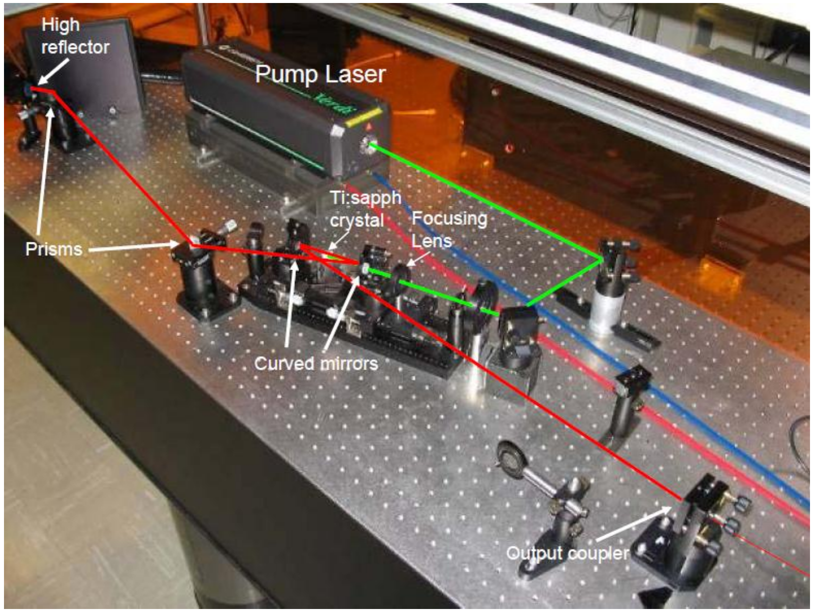
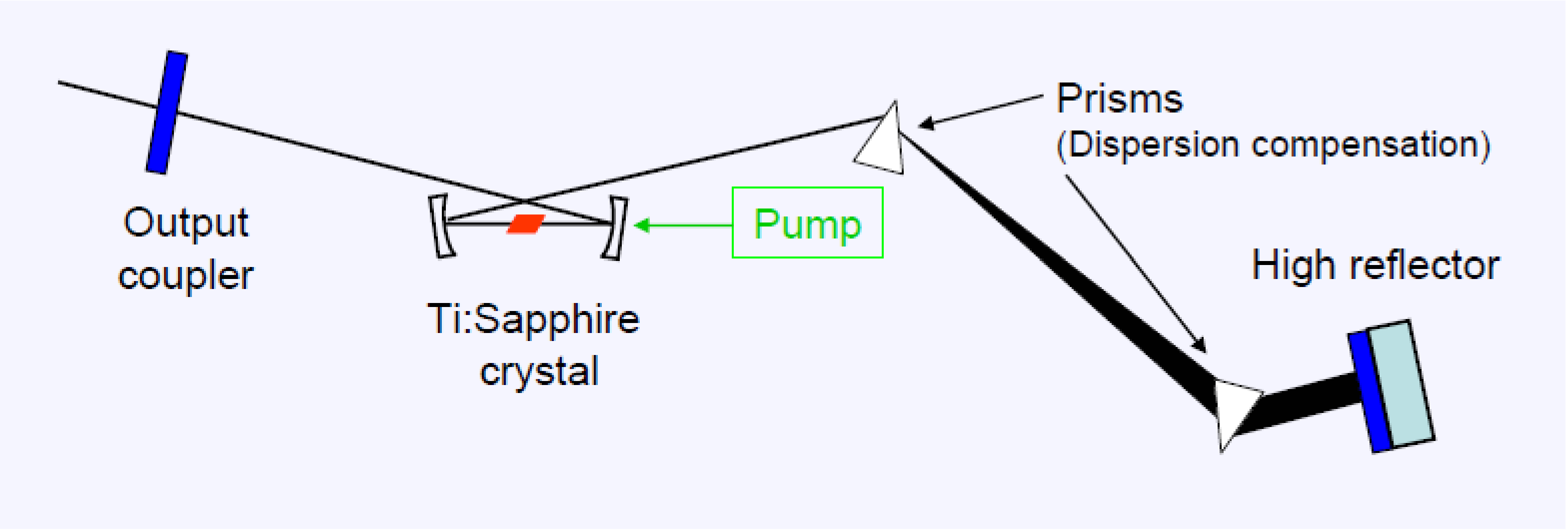
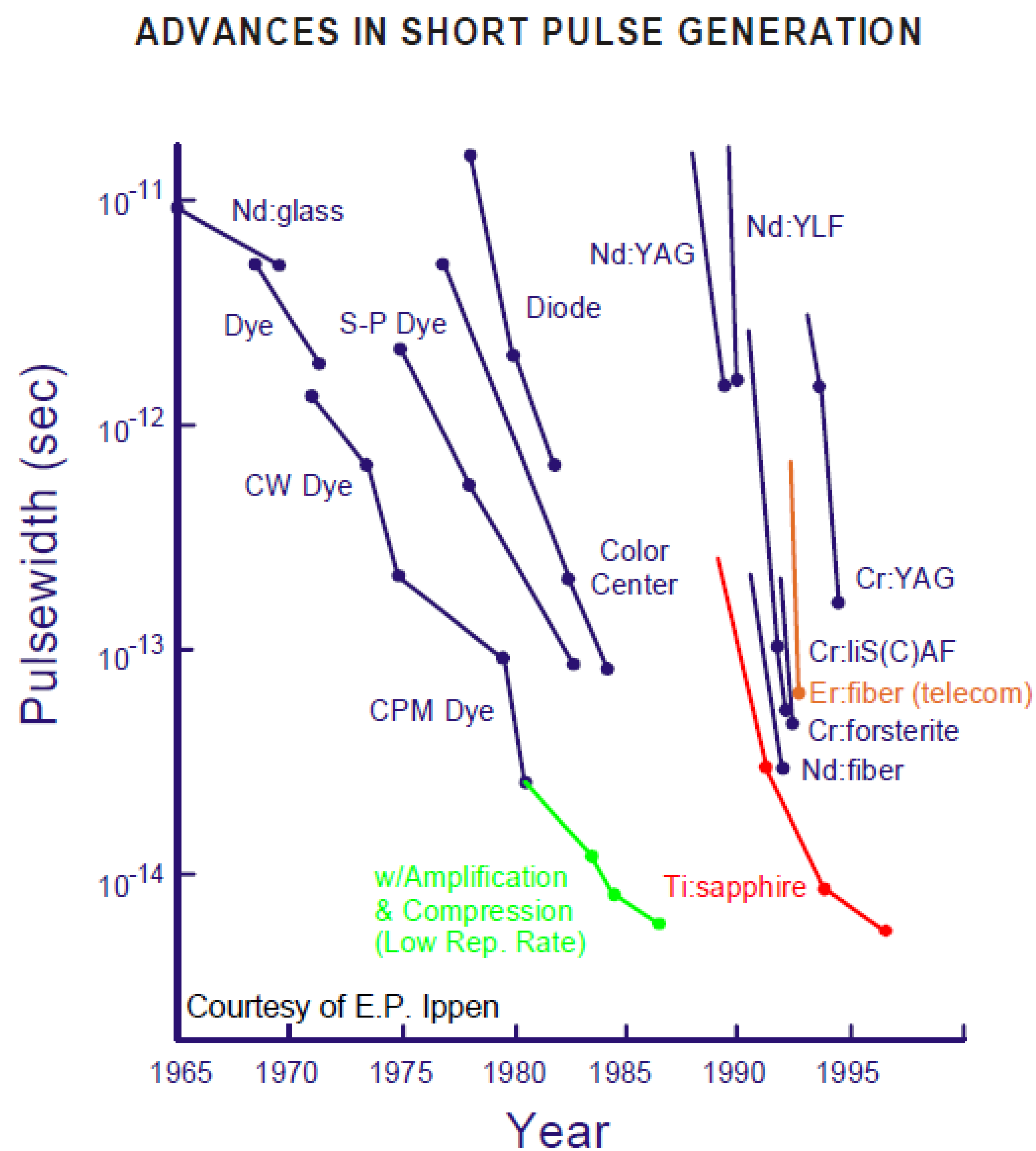


Figure 1

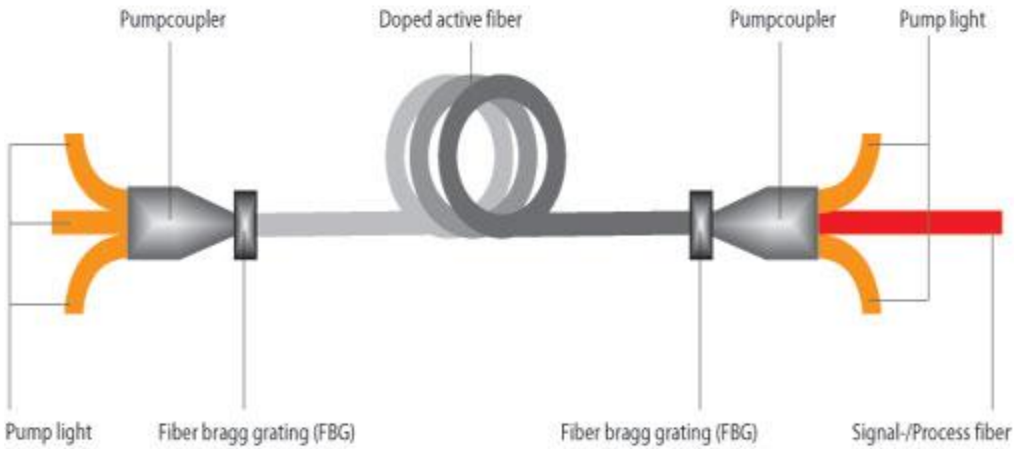


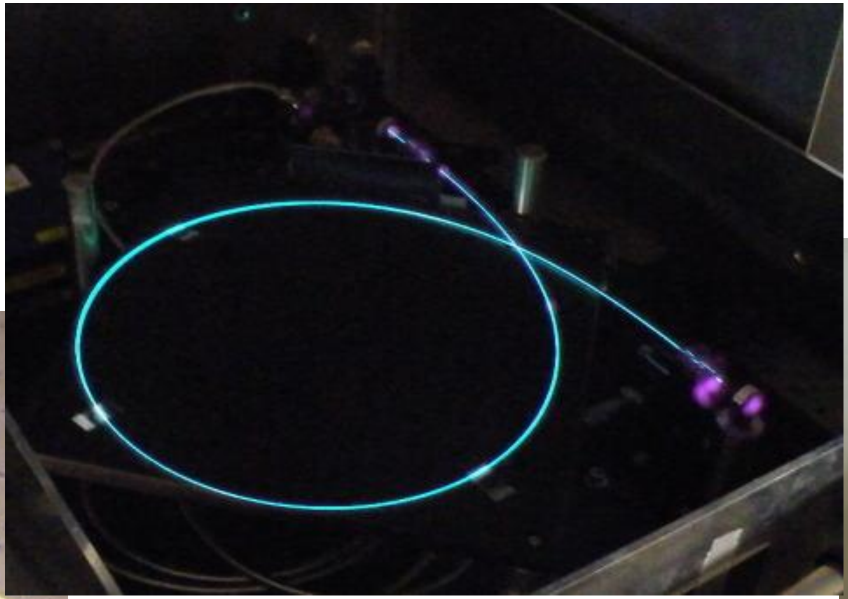


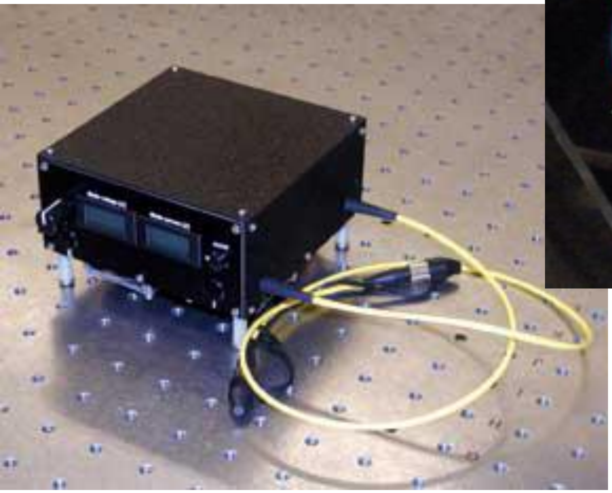
Historical Progress in Ultrashort Pulses



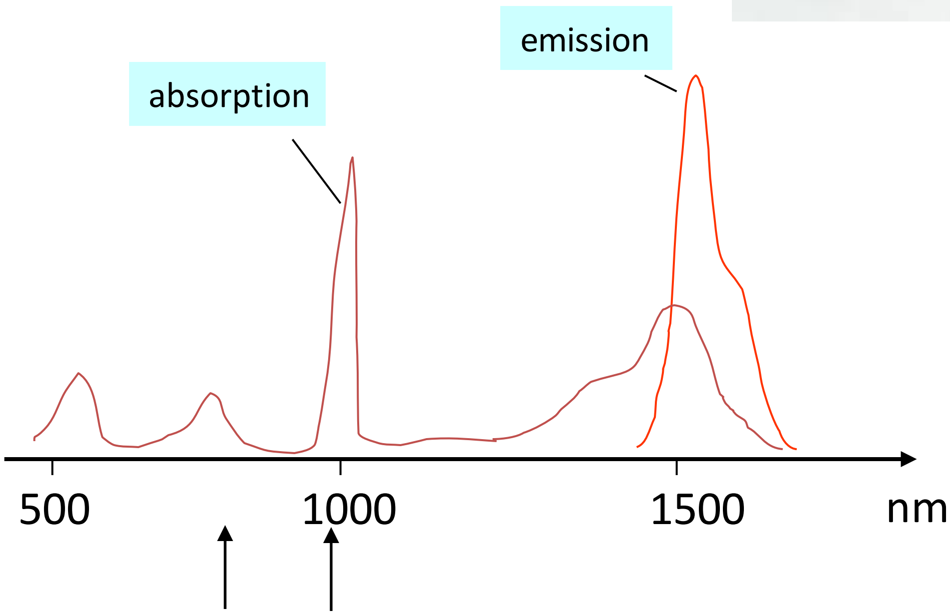
Fiber Lasers (e.g. rare-earth doped silica fiber)





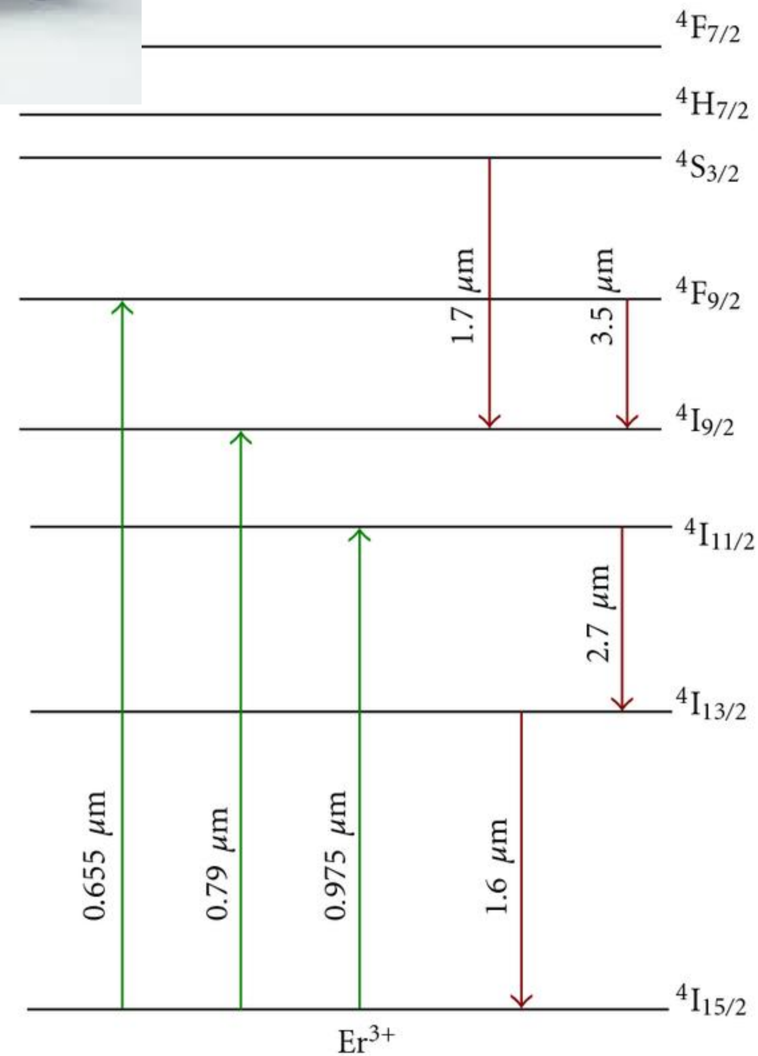


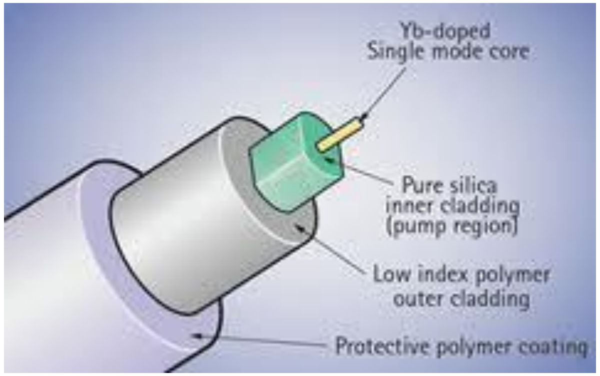
erbium-doped glass fibers

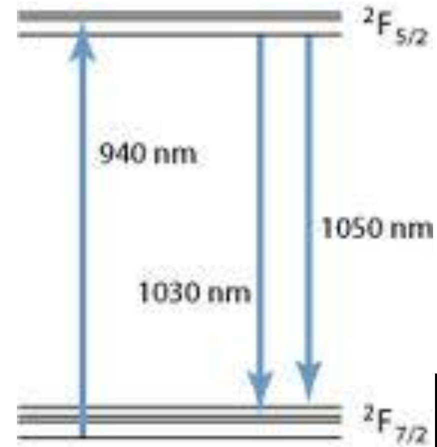


pumping with diode lasers is possible

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

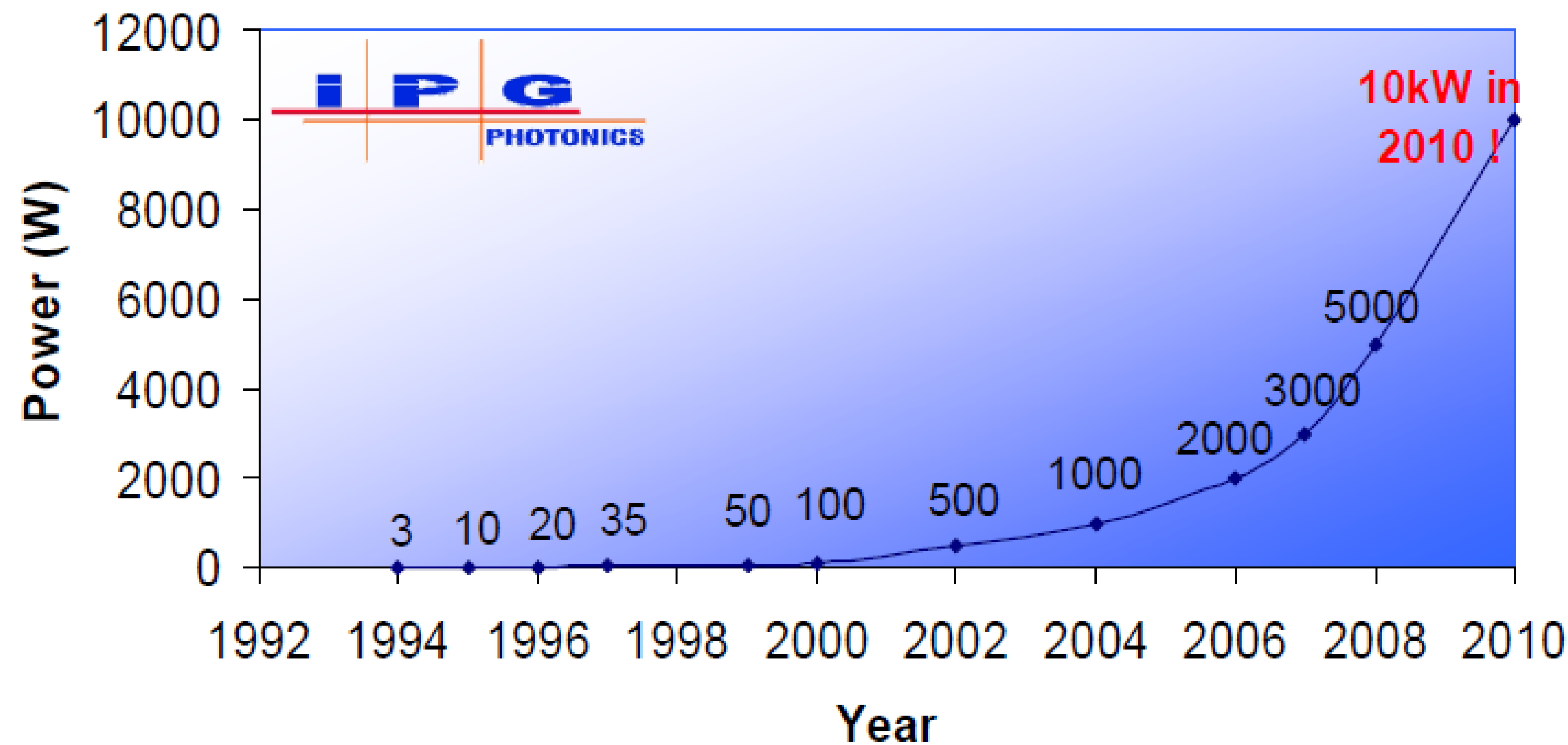






Growth of Yb:HPFL SM

(near diffraction limited)



IPG Fiber Lasers

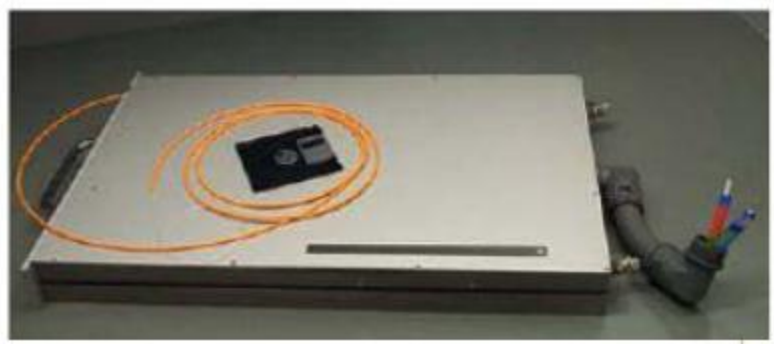
A single module can supply:

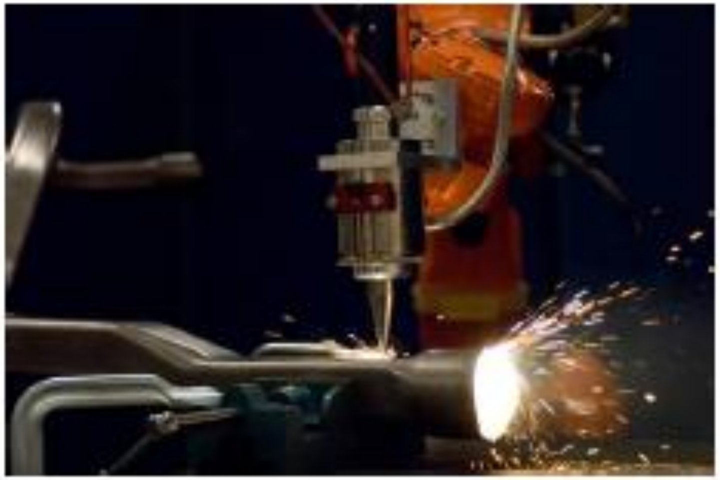
- 250, 400, 800, 1000+ W of laser power
- Wavelength of 1070nm (NIR)
- One 7 or 15 um fiber core
- 0.34-0.41mm*mrad beam divergence

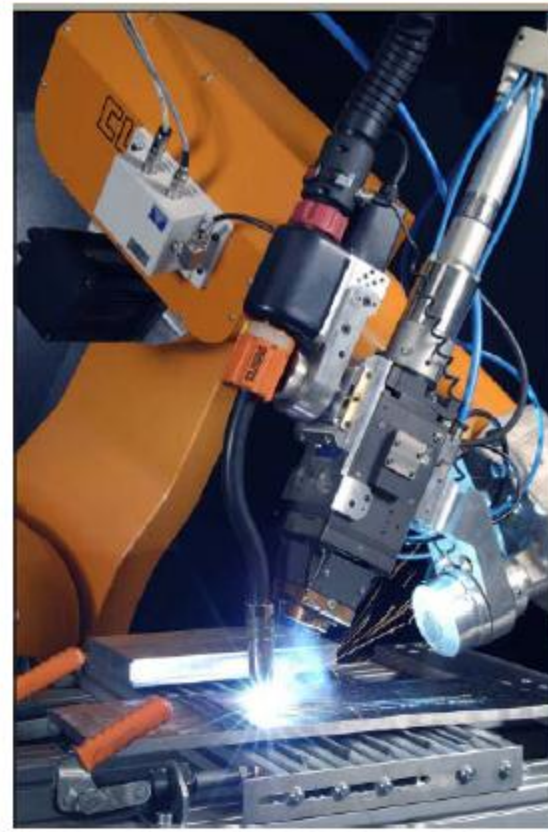
T x H x D = 60 x 33 x 4.7 cm

Efficiency (DC) > 35%

Building blocks (modules) for HPFLs







ALAW 2009

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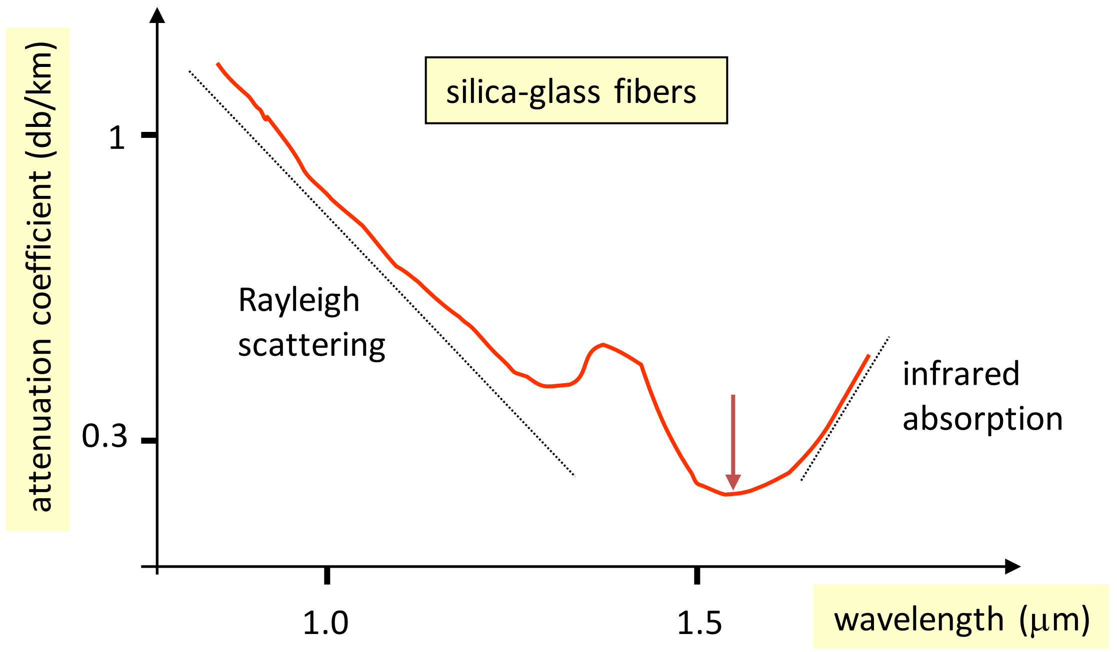
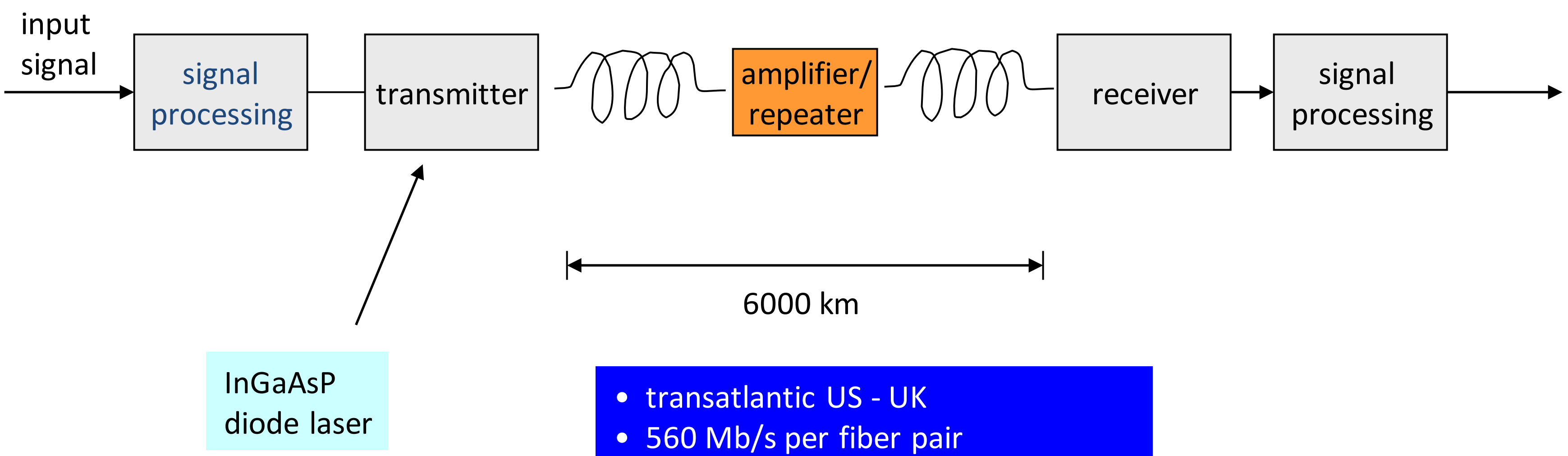
11.3 Fiber-optic Communications

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



- 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

Examples:

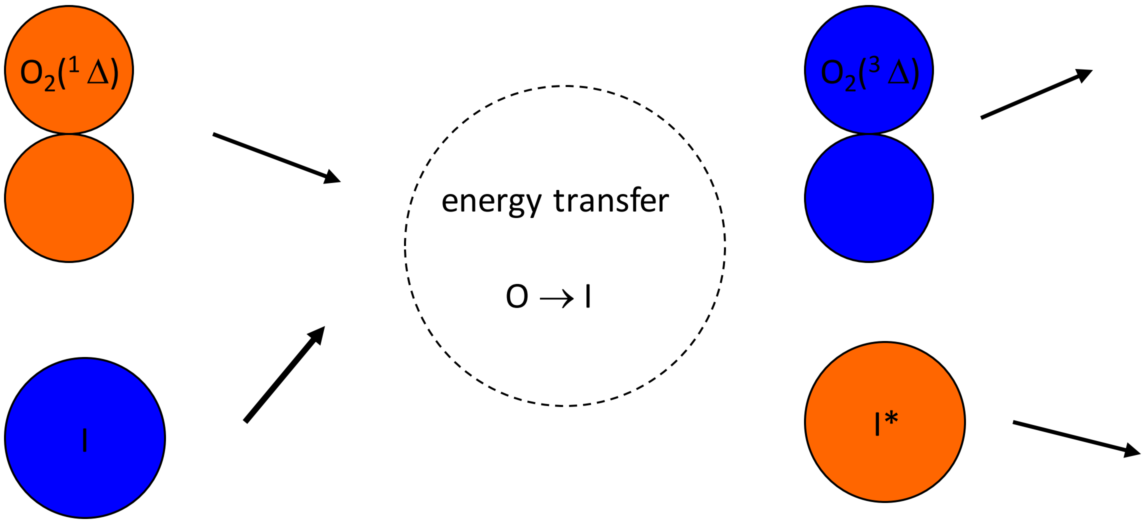
reaction	active medium	wavelength
$F + D_2 \rightarrow DF^* + D$	DF	3.5 - 4.1 μm
$Cl + HI \rightarrow HCl^* + I$	HCl	3.5 - 4.1 μm
$H + Br_2 \rightarrow HBr^* + Br$	HBr	4.0 - 4.7 μm
$F + H_2 \rightarrow HF^* + H$	HF	3.5 - 4.1 μm
$I + O_2^* \rightarrow I^* + O_2$	I	1.31 μm

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

12.2 The chemical oxygen-iodine laser

chemical reaction:

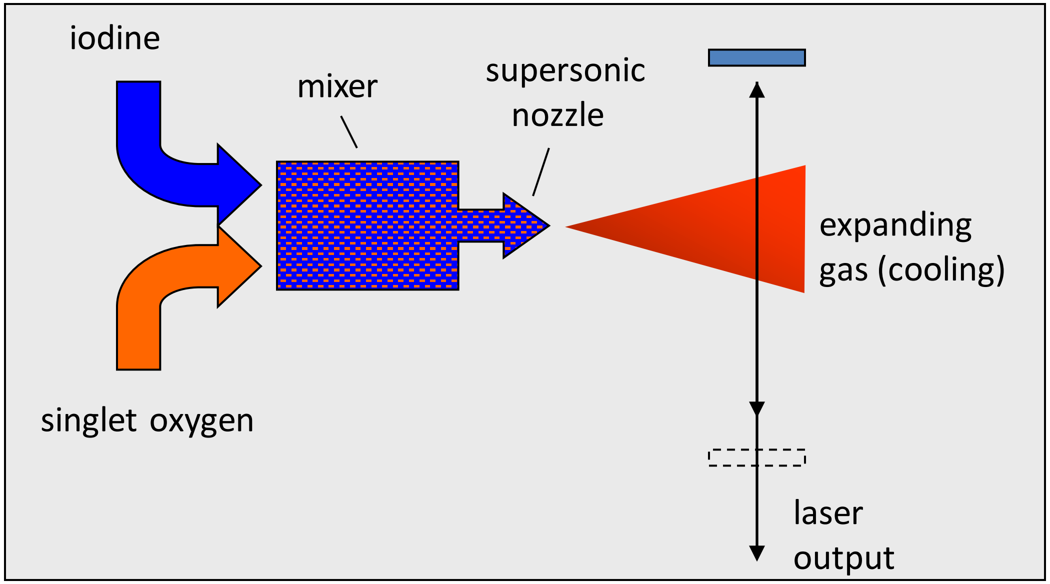
$O_2(^1\Delta) + I \leftrightarrow O_2(^3\Sigma) + I^*$



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

1 km propagation in atmosphere