Lasers

lecture 11

Czesław Radzewicz

solid state lasers (excluding semiconductor lasers)

matrix + dopant

isolators=crystals + glass + ceramics

transient metals
rare earth metals

Matrix:

oxides:
sapphire (Al_2O_2)
alexandrite ($BeAl_2O_4$)
YAG – alumimium itrium garnet ($Y_3Al_5O_{12}$)
………

fluorides:
LISAF ($LiSrAlF_6$)
YLF ($YLiF_4$)
………

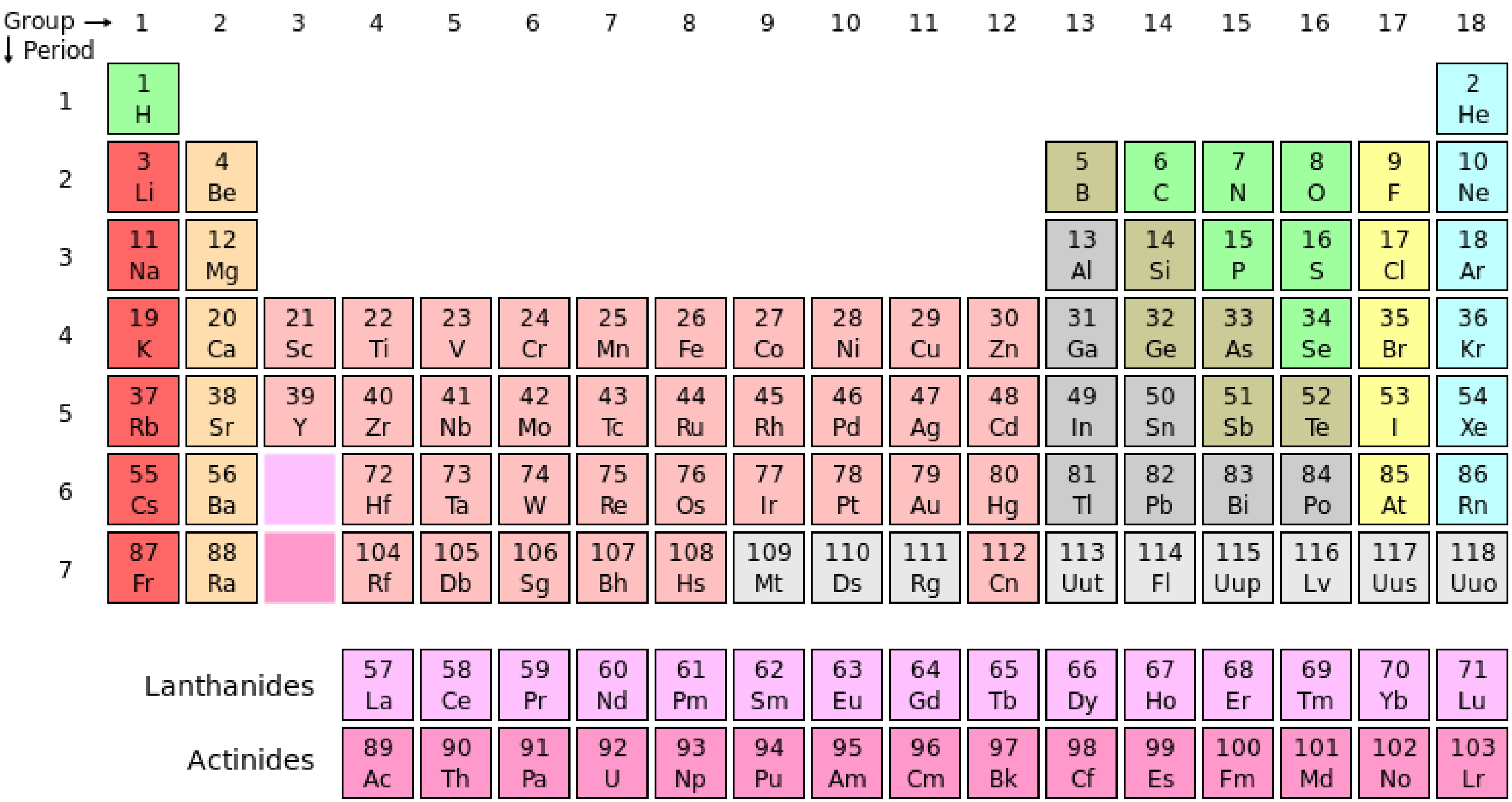
tungstate
$KY(WO_4)_2$
$KGd(WO_4)_2$
…………

Important parameters:

- bandgap
- thermal conductivity
- thermal lensing $\frac{dn}{dT}$
- mechanical properties
- FOM , $\mathrm{FOM} = \frac{\alpha_p}{\alpha_l}$

dopants

- transient metals
- lanthanides

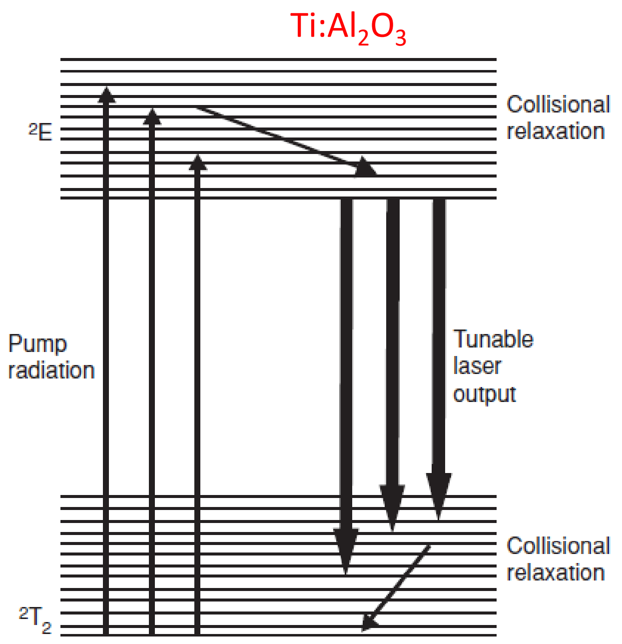


dopants

Transient metals: atoms with the d shell partially empty

example: $Ti: Al_2O_3$

Electronic configuration of Ti: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^2 4s^2 \ = \ Ar + 3d^2 4s^2$
In sapphire crystal the titanium atoms sheds 3 electrons to become Ti^{3+} with electronic configuration $Ar \ + \ 3d^1$
Optical transitions – excitations of the $3d$ electron
The $3d$ electron occupies an external shell and thus its energy levels are sensitive to external perturbations. In effect, the transitions frequencies depend on the crystal matrix and strong coupling with phonons is observed



Lanthanides: atoms with the f shell partially empty

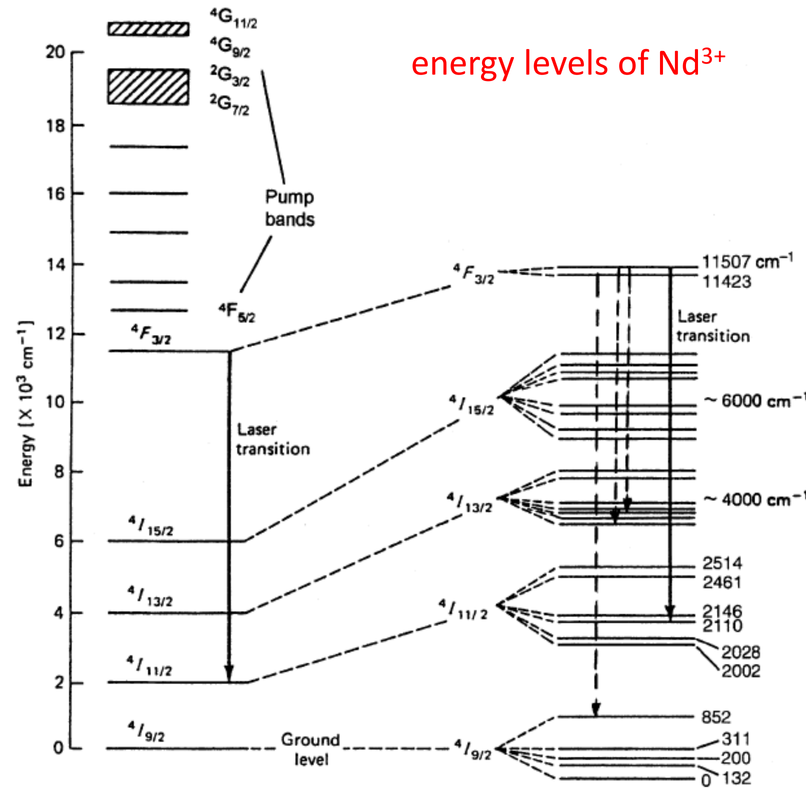
example : $Nd: YAG$

Electronic configuration of Nd atom : $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 \, 4p^6 4d^{10} 4f^4 5s^2 5p^6 6s^2 \ = \ Xe + 4f^4 5s^2 5p^6 6s^2$
Nd^{3+} ion has electronic configuration: $Xe + 4f^3 5s^2 5p^5$; optical transitions correspond to excitations of the f electron. It occupies $4f$ shell which is well shielded by $5s$, $5p$ and $6s$ outer electrons.
Frequencies of optical transitions are not very sensitive to the matrix.
Nd:YAG λ_l=1,064 μm
Nd:YLF λ_l=1,047 μm

neodymium doped materials

$$Nd\!:\!YAG \;-\; Y_3Al_5O_{12}\!:\!Nd^{3+}$$
$$Nd\!:\!YLF \;-\; YLiF_4\!:\!Nd^{3+}$$
….

energy levels of Nd^{3+}



	YAG	YLF	glass
thermal conductivity, W/(m·K)	13	6	0.8
dn/dT [1/K]	$7\cdot10^{-6}$	$4.3\cdot10^{-6}$ $2\cdot10^{-6}$	$2\cdot10^{-6}$
τ [μs]	230	480	800
λ_l [μm]	1.064	1.047	1.059
σ [cm²]	$1.8\cdot10^{-19}$	$2.4\cdot10^{-19}$	
$\Delta\nu$ [cm⁻¹]	≈6	≈6	≈300

Nd:YAG

energetic structutre of Nd^{3+}

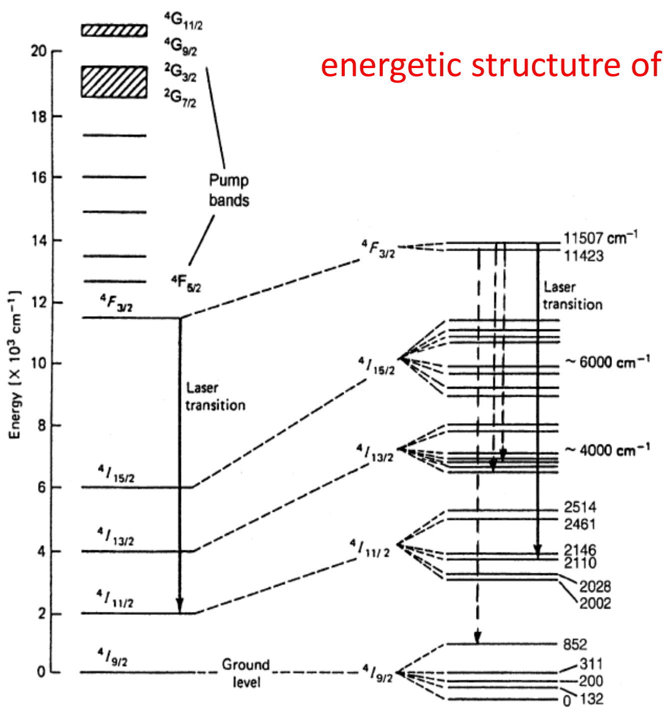


Table 2.2. Physical and optical properties of Nd:YAG

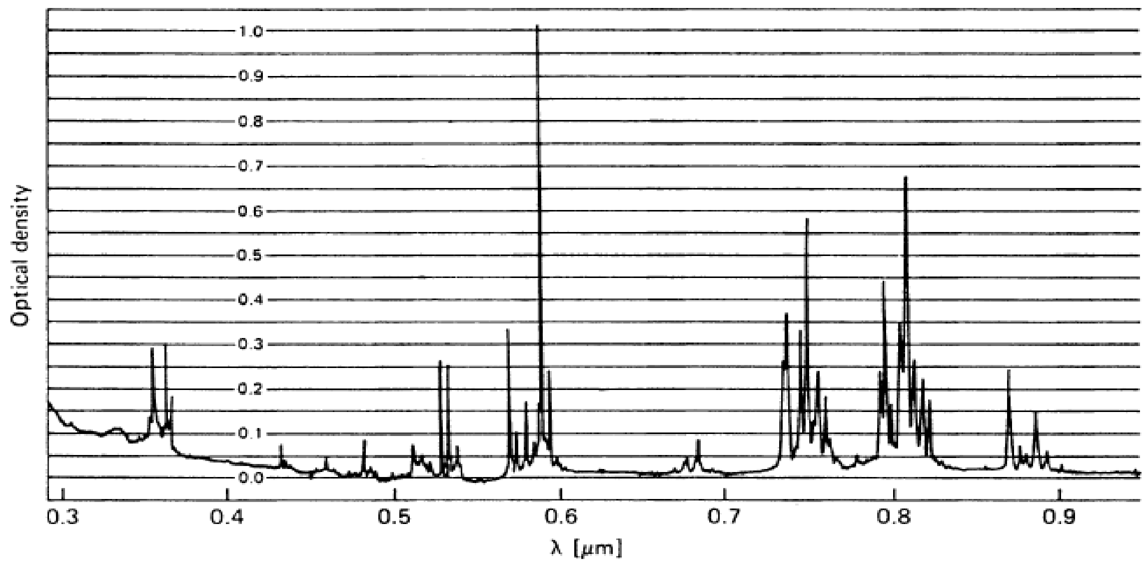
Chemical formula	$Nd{:}Y_3Al_5O_{12}$
Weight % Nd	0.725
Atomic % Nd	1.0
Nd atoms/cm^3	1.38×10^{20}
Melting point	1970°C
Knoop hardness (kg/mm^2)	1320
Density	4.56 g/cm^3
Tensile strength	200 MPa
Modulus of elasticity	310 Gpa
Poisson ratio	0.30
Thermal expansion coefficient	
[100] orientation	8.2×10^{-6}/°C,
[110] orientation	7.7×10^{-6}/°C,
[111] orientation	7.8×10^{-6}/°C,
Linewidth	120 GHz
Stimulated emission cross section	
$R_2 - Y_3$	$\sigma = 6.5 \times 10^{-19}$ cm^2
$^4F_{3/2} - {}^4I_{11/2}$	$\sigma = 2.8 \times 10^{-19}$ cm^2
Fluorescence lifetime	230 μs
Photon energy at 1.06 μm	$h\nu = 1.86 \times 10^{-19}$ J
Index of refraction	1.82 (at 1.0 μm)

Nd:YAG

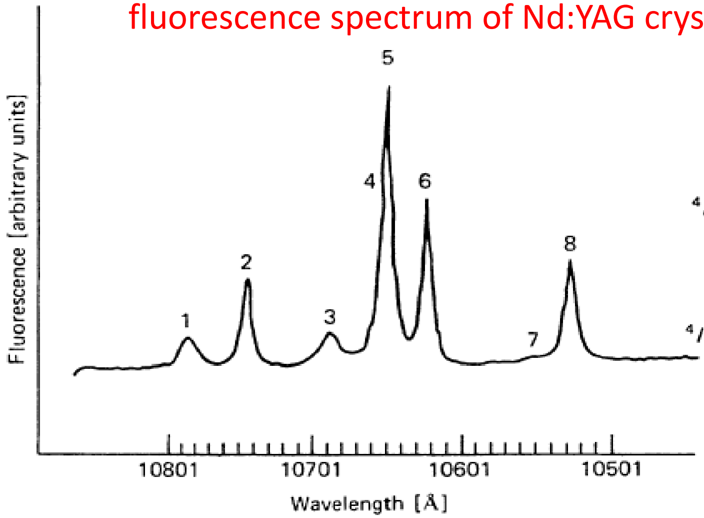
Laser crystals are pumped by:

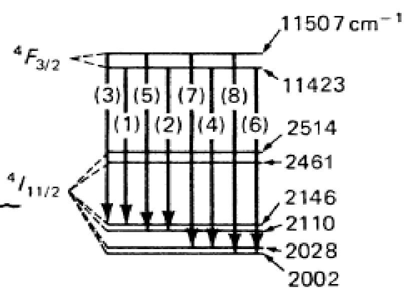
- another laser
- flash lamp
- sunlight
- ????

absorption spectrum of Nd:YAG crystal



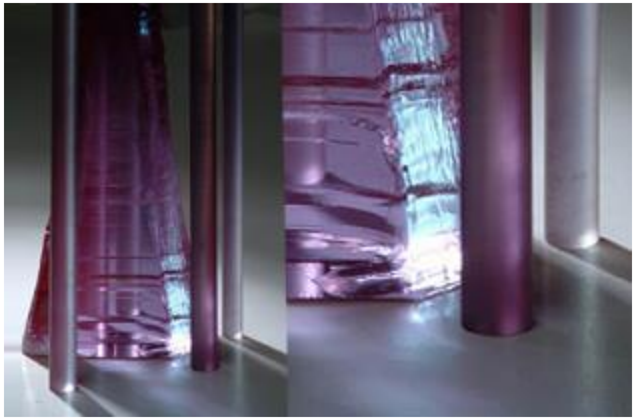
fluorescence spectrum of Nd:YAG crystal





alexandrite

$BeAl_2O_4:Cr^{3+}$



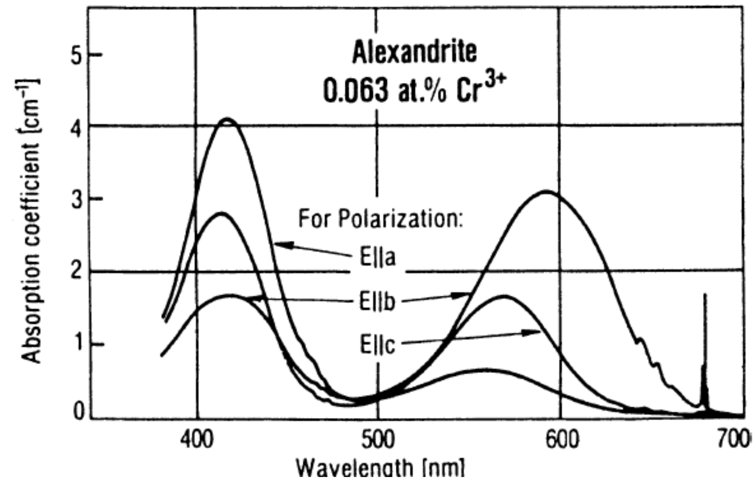
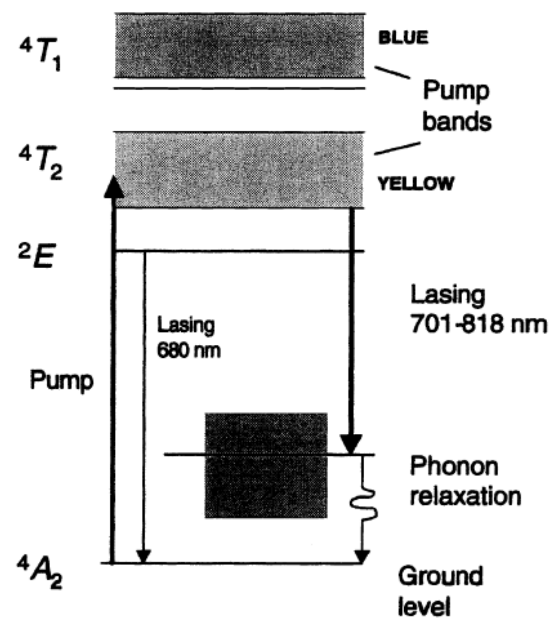


Table 2.9. Material parameters of alexandrite

Laser wavelength (nm)	700–818
Stimulated emission cross section (cm^2)	1.0×10^{-20}
Spontaneous lifetime (μs)	260 ($T = 298$ K)
Doping density (at.%)	0.05–0.3
Fluorescent linewidth (nm)	100
Gain coefficient for 1 J/cm^3 stored energy (cm^{-1})	0.038–0.19
Index of refraction (750 nm)	$E\|\|b$ 1.7421
Thermal expansion	$\|\|b$ 6.1×10^{-6} /K
Thermal conductivity (W/cm K):	0.23
Melting point (°C)	1870
Hardness (kg/mm^2)	2000

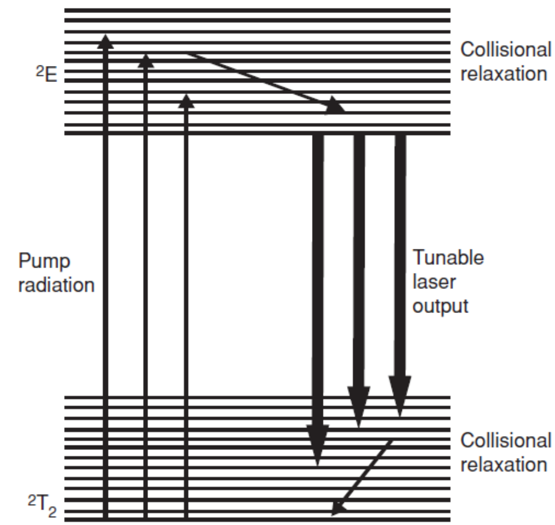


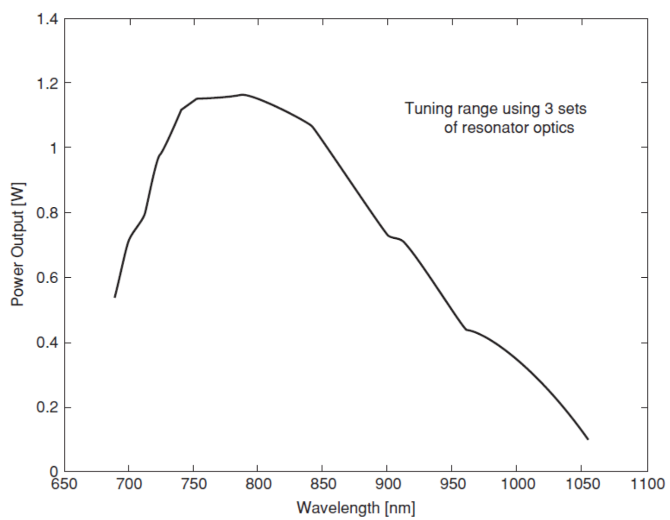
saturating fluence 40J/cm^2 !

Ti:Sapphire

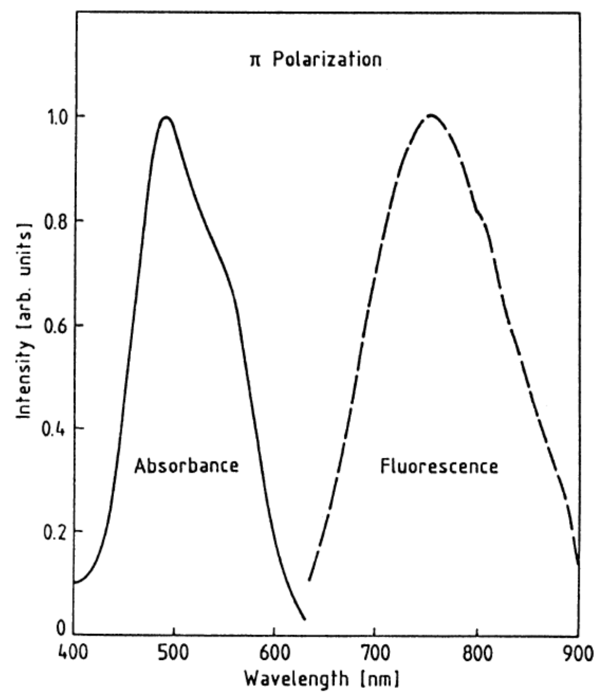
$Al_2O_3:Ti^{3+}$

Index of refraction	1.76
Fluorescent lifetime	3.2 μs
Fluorescent linewidth (FWHM)	230 nm
Peak emission wavelength	780 nm
Peak stimulated emission cross section	
parallel to *c*-axis	$\sigma_{\|\|} \sim 4.1 \times 10^{-19}$ cm^2
perpendicular to *c*-axis	$\sigma_{\perp} \sim 2.0 \times 10^{-19}$ cm^2
Stimulated emission cross section	
at 0.795 μm	$\sigma_{\|\|} = 2.8 \times 10^{-19}$ cm^2
Quantum efficiency of converting a 0.53 μm photon into an inverted site	$n_Q \approx 1$
Saturation fluence at 0.795 μm	$E_s = 0.9$ J/cm^2



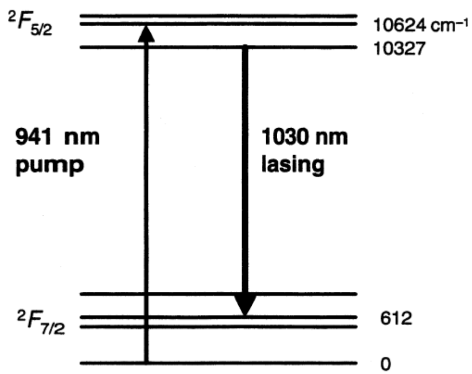


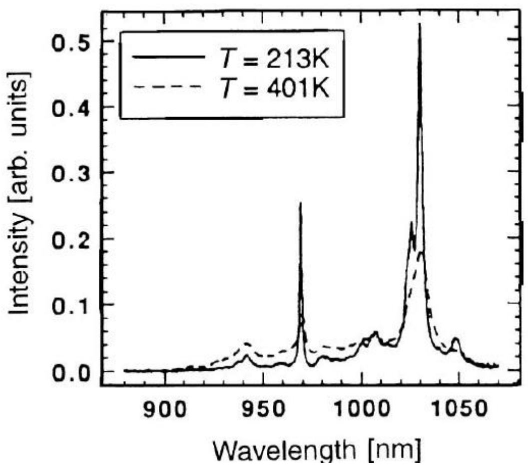
tuning range 690-1060 nm !



ytterbium doped laser materials

np. Yb^{3+}:YAG



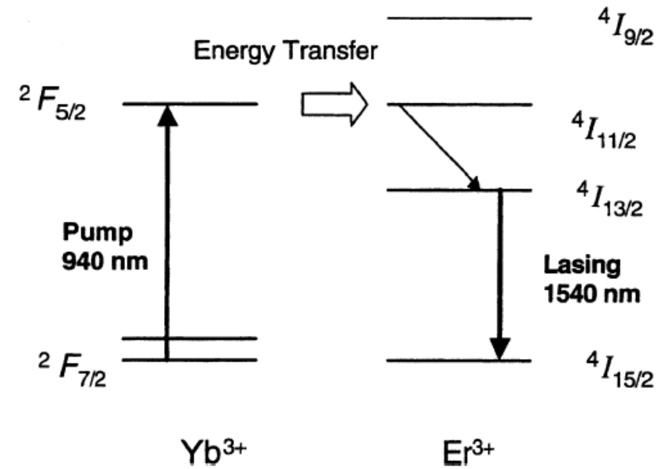


Laser wavelength	1030 nm
Radiative lifetime at room temperature	951 μs
Peak emision cross section	2.1×10^{-20} cm^2
Peak absorption wavelength	941 nm
Pump bandwidth at 941 nm	18 nm
Doping density (1% at.)	1.38×10^{20} cm^3

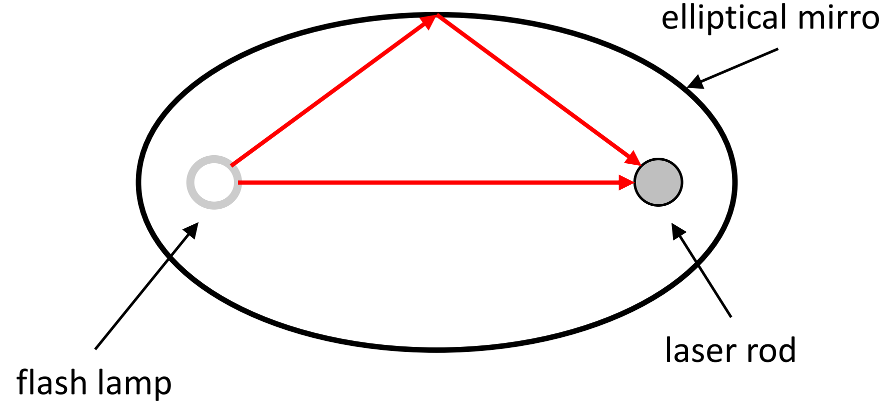
very small Stokes shift

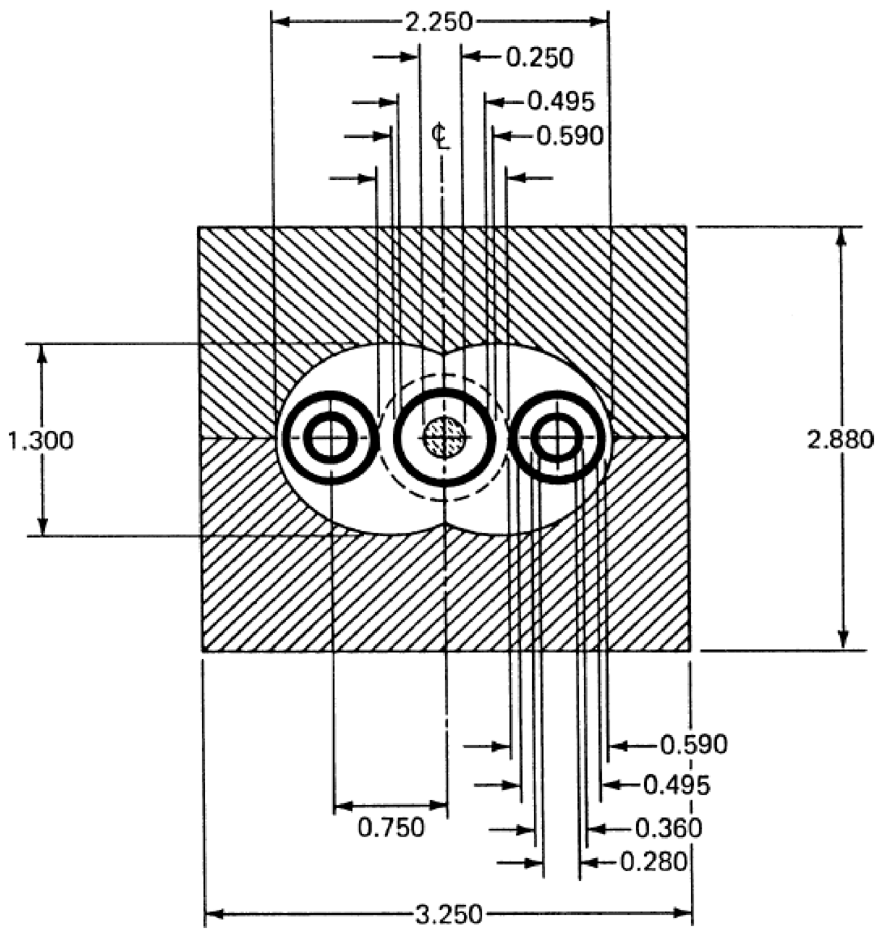
erbium doped laser materials

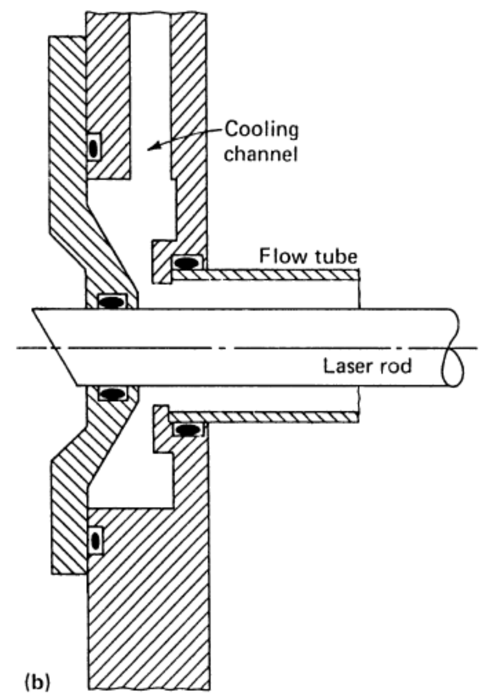
EDA (Erbium Doped Amplifier)
fiber oscillators and amplifiers



Nd:YAG – flash lamp pumping







(b)

Nd:YAG – flash lamp pumping, 2

Let's normalize Nd:YAG absorption spectrum and the flash lamp emission spectrum:
$\int \sigma_a(\lambda)\, d\lambda = 1,\ \int \sigma_e(\lambda)\, d\lambda = 1$

Then the overlap integral

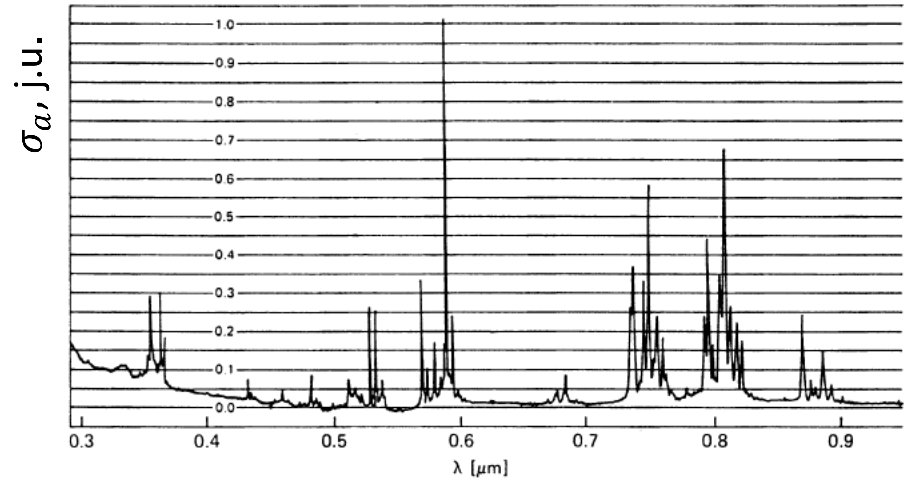
$$\eta_p = \int \sigma_e(\lambda)\sigma_a(\lambda)d\lambda \leq 1$$

Is a good measure of how well the lap's spectrum matches the absorption spectrum.
In the case of Nd:YAG crystal and a krypton lamp (the best available) we have

$$\eta_p \ll 1$$

In addition the short wavelength part of the spectrum absorber by the crystal heats it up.

Nd:YAG crystal absorption spectrum



emission spectrum of the krypton lamp

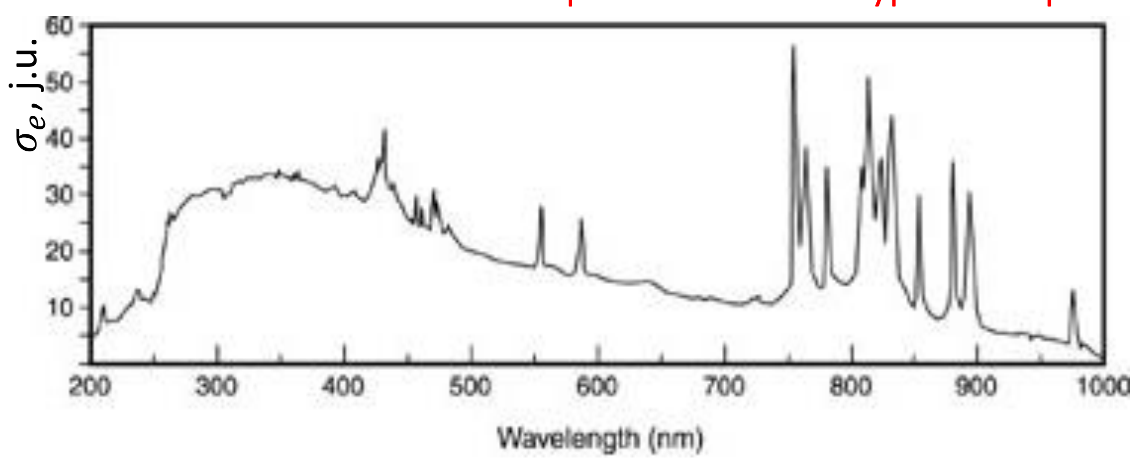
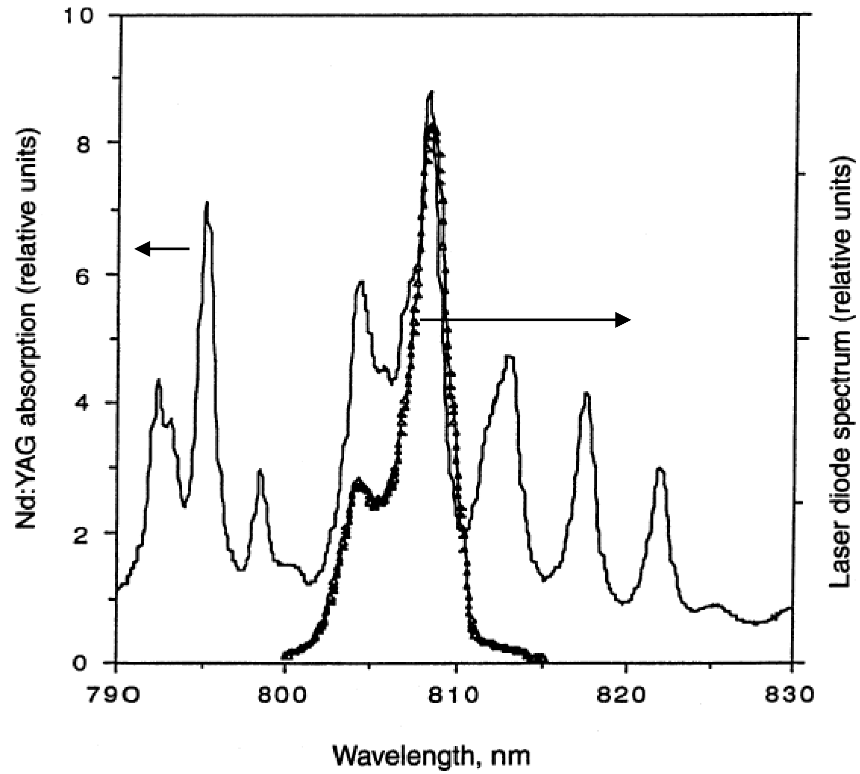


Table 6.5. Energy transfer in a cw krypton arc lamp, pumped Nd:YAG laser

Heat dissipation of lamps	55%
Heat dissipation of pump reflectors	30%
Power absorbed by coolant and flow tubes	7%
Heat dissipation by rod	5%
Laser output	2%
Fluorescence output	0.4%
Optical losses	0.6%
Power absorbed by laser rod	8%
Electrical input to lamps	100%

Nd:YAG – diode pumping

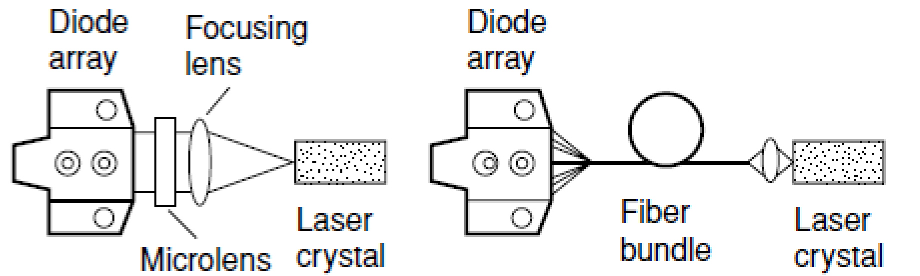


The absorptions spectrum of Nd:YAG is typical for most laser crystals – it consists of many narrow peaks with little absorption in between. It is a much better strategy to use a narrowband source with the wavelength matched to one of the peaks.

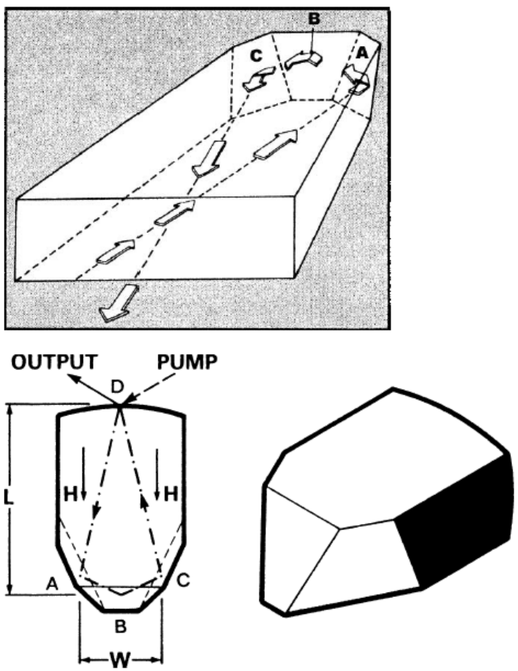
gain medium	λ_p [nm]	diode laser
Nd:YAG	808	GaAlAs
Yb:YAG	941	InGaAs
Nd:YVO_4	809	GaAlAs
Nd:YLF	798	GaAlAs
Cr:LiSAF	670	AlGaInP (low power!)
Yb:KYW	975	InGaAs

Nd:YAG – diode pumping, 2

longitudinal pumping

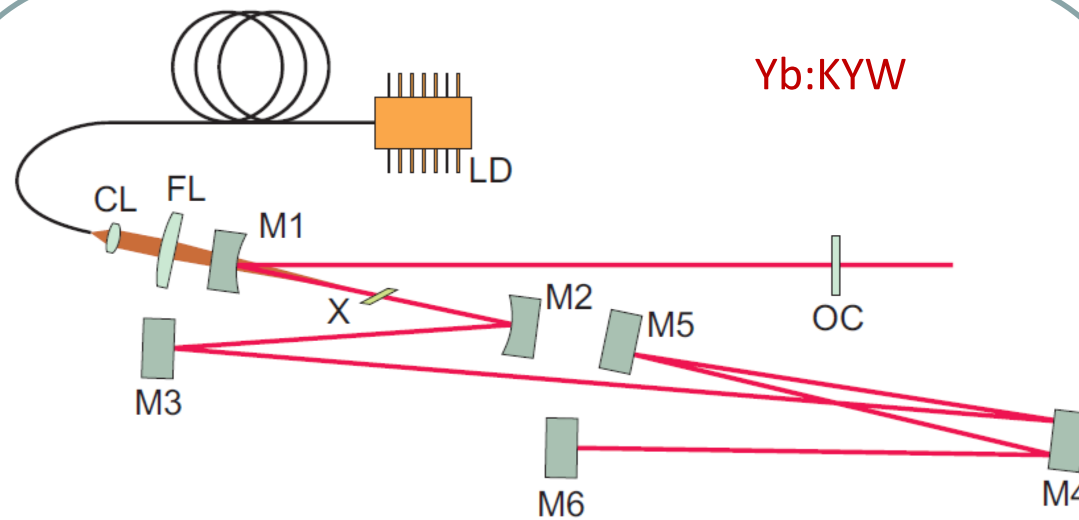


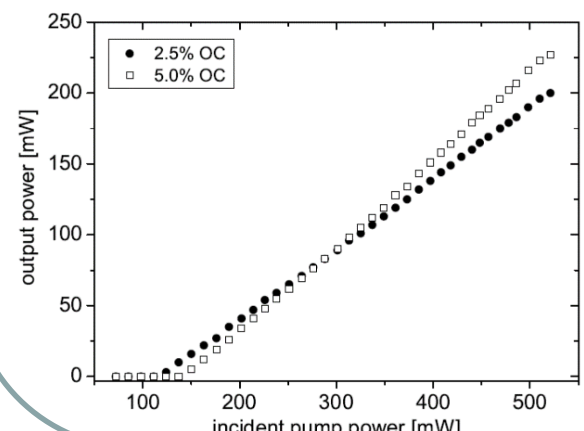
monolithic Nd:YAG laser



T. J. Kane, R. J. Byer, Opt. Lett. **10**, 65 (1985)

Yb:KYW





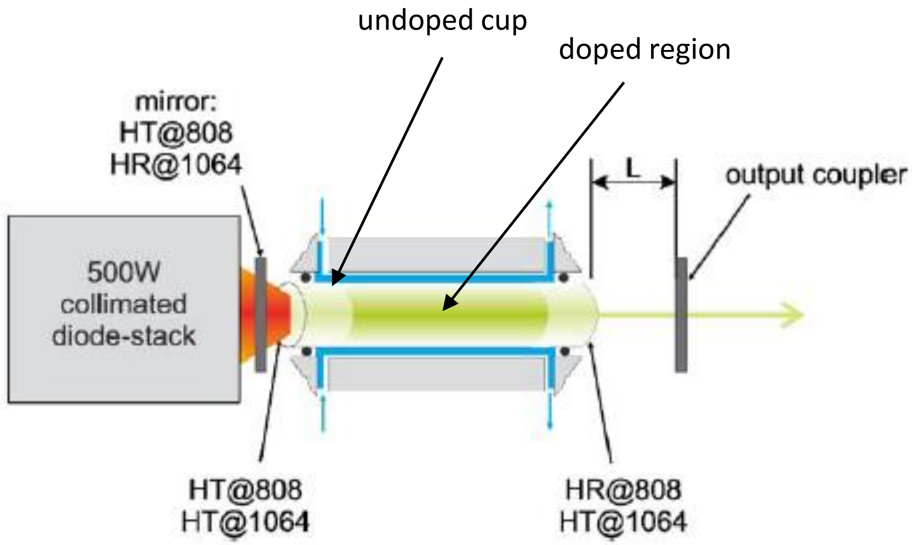
P. Wasylczyk and C. Radzewicz, Laser Physics **19**, 129 (2009)

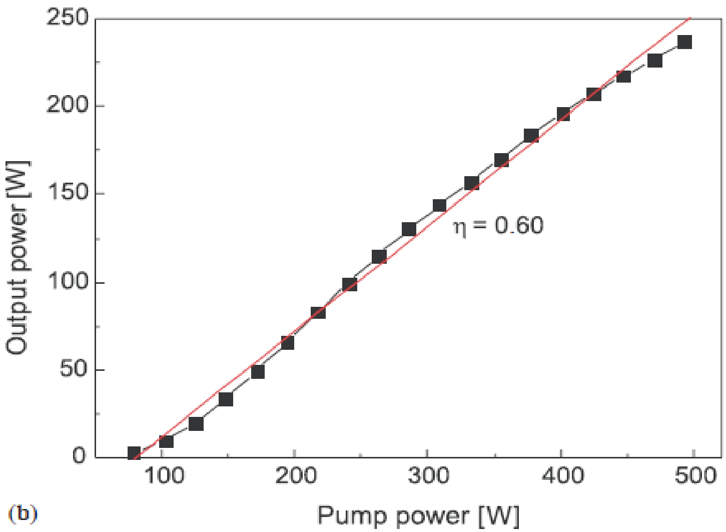
Nd:YAG – diode pumping, 3

Compact high-power end-pumped Nd:YAG laser

Maik Frede*, Dietmar Kracht, Martin Engelbrecht, Carsten Fallnich

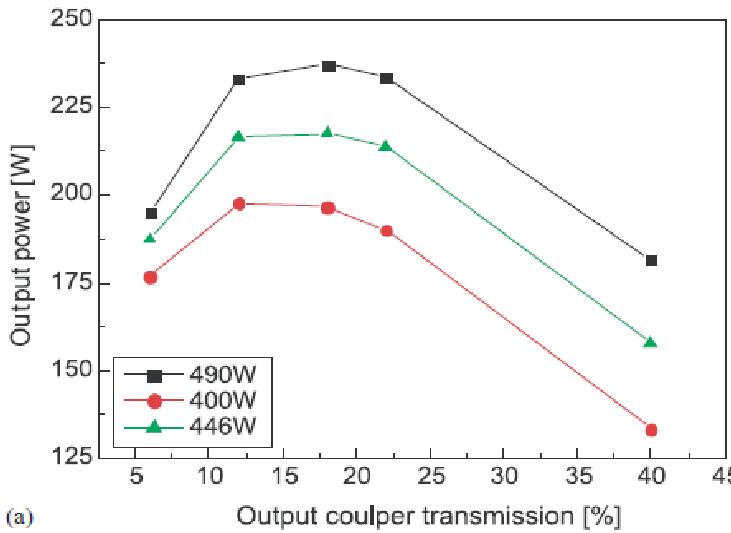
Optics & Laser Technology 38 (2006) 183–185





(b)

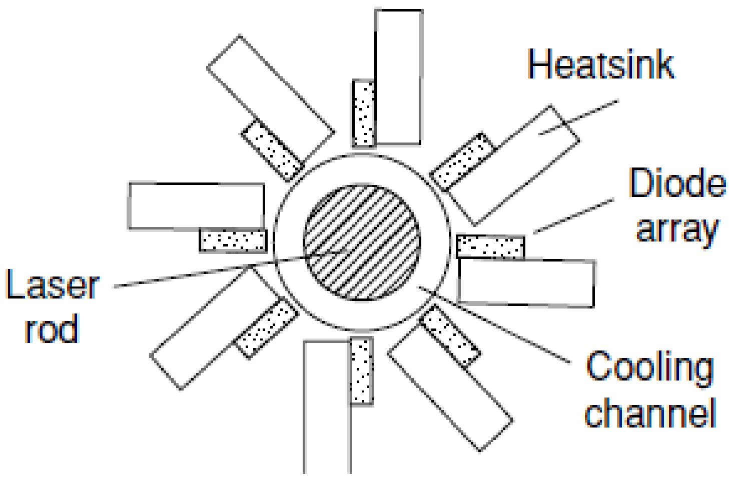
efficiency	48%
slope efficiency	60%

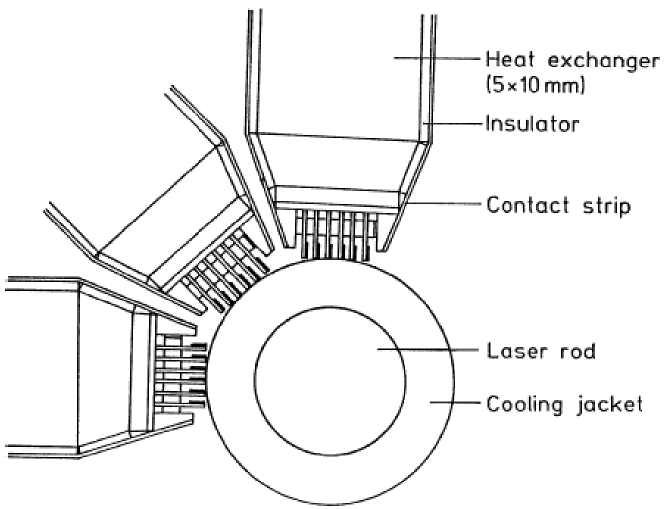


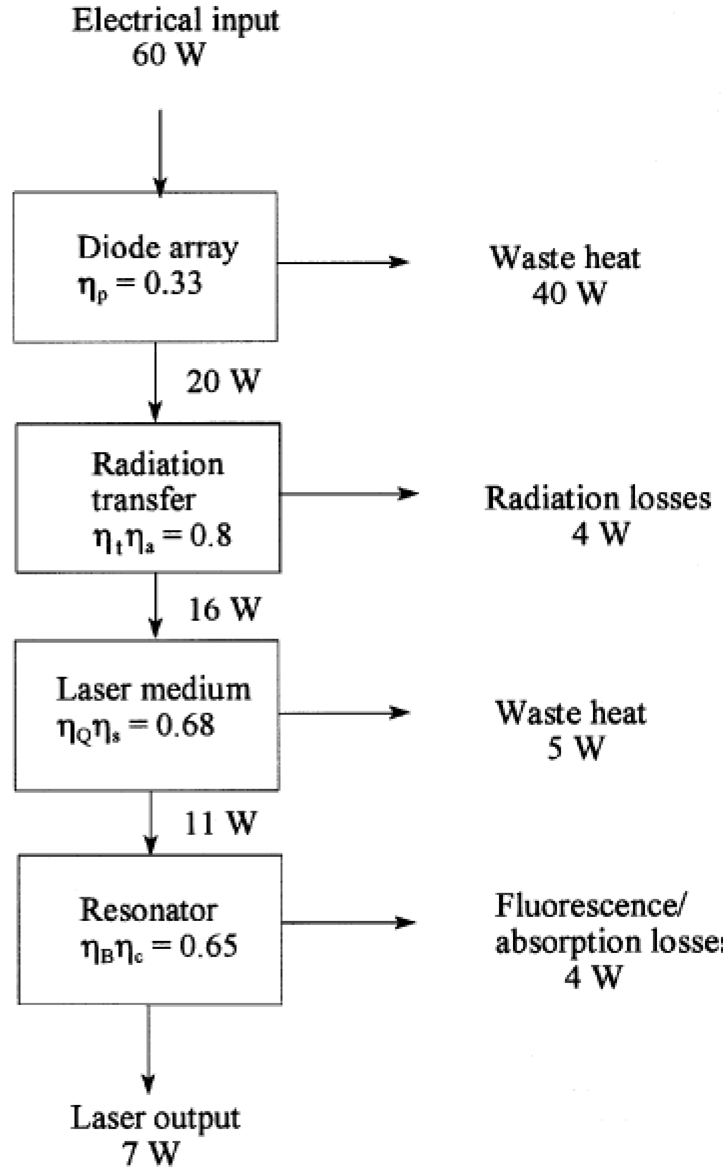
(a)

- the cups allow to cool uniformly all the pumped part of the crystal
- diode laser 550W, 3x4mm^2, NA=0.42
- the rod has a polished cylindrical Surface and acts as waveguide for the pump beam
- double-pass of the pump beam – small gain gradient along the crystal axis
- poor quality of the output beam, M^2=80

Nd:YAG – diode pumping, 4







commercial Diode-Pumped Solid State Laser (DPSSL)

COHERENT

	Evolution-15	Evolution-30	Evolution-45	Evolution-HE
Wavelength (nm)	527	527	527	527
Pulse Repetition-Rate (kHz)		1 to 10		1 (factory set)[1]
Average Output Power (W)	12 at 1 kHz 15 at 5 kHz 15 at 10 kHz	20 at 1 kHz 30 at 5 kHz 30 at 10 kHz	28 at 1 kHz 45 at 5 kHz 45 at 10 kHz	45 at 1 kHz 75 at 5 kHz 75 at 10 kHz
Energy-Per-Pulse (mJ)	12 at 1 kHz 3 at 5 kHz 1.5 at 10 kHz	20 at 1 kHz 6 at 5 kHz 3 at 10 kHz	28 at 1 kHz 9 at 5 kHz 4.5 at 10 kHz	45 at 1 kHz 15 at 5 kHz 7.5 at 10 kHz
Typical Pulse Width (nsec)(FWHM)	<300 at 1 kHz	<250 at 1 kHz	<250 at 1 kHz	<150 at 1 kHz
Pulse-to-Pulse Energy Stability (% rms)		<1		<1
Polarization Ratio		Horizontal, >100:1		Horizontal, >100:1
Spatial Mode		Multimode		Multimode
Beam Divergence (mrad)(full angle)		<10		<8
Beam Circularity (%)		>80		>80
Nominal Beam Diameter at Output Window (mm)($1/e^2$)		3		3

comercial flashlamp-pumped solid state laser

Continuum®
The High Energy Laser Company™

Q-switched lasers

Powerlite DLS 8000 Specifications

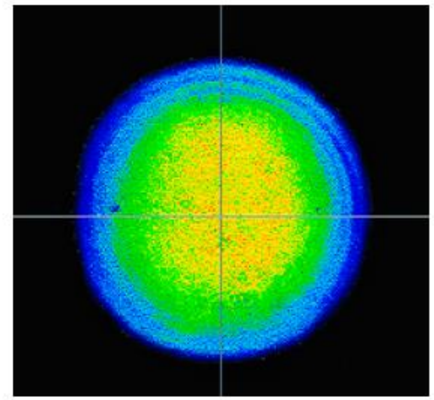
Description	8000	8010	8020	8030	8050
Repetition Rate (Hz)	10	10	20	30	50
Energy (mJ)					
1064 nm	1200	1650	1200	650	550
532[1] nm	600	800	550	300	210
355[2] nm	310	450	300	150	95
266 nm	120	150	80	50	30
Pulsewidth[3] (nsec)					
1064 nm	6-8	6-8	6-8	7-9	7-9
532 nm	5-7	5-7	5-7	6-8	6-8
355 nm	5-7	5-7	5-7	6-8	6-8
266 nm	5-7	5-7	5-7	6-8	6-8
Linewidth[4] (cm^{-1})					
Standard	1	1	1	1	1
Injection Seeded, SLM	0.003	0.003	0.003	0.003	0.003
Divergence[5] (mrad)	0.45	0.45	0.45	0.5	0.5
Beam Pointing Stability[6] (±µrad)	30	30	30	30	30
Beam Diameter	9	9	9	7	7

comercial flashlamp-pumped solid state laser, 2

Continuum®
The High Energy Laser Company™

Powerlite DLS 2 J Specifications

Description	2 J
Repetition Rate (Hz)	10
Energy (mJ)	
1064 nm	3500
532[1] nm	2000
Pulsewidth[2] (nsec)	
532 nm	4-8
Linewidth[3] (cm^{-1})	
Standard	1
Injection Seeded, SLM	0.003
Divergence[4] (mrad)	0.45
Beam Pointing Stability[5] (±μrad)	30
Beam Diameter (mm)	12
Jitter[6] (±ns)	
Unseeded	0.5
Seeded	1.0
Energy Stability[7] (±%)	
532 nm	3.0;1.0
Power Drift[8] (±%)	
532 nm	6.0
Beam Spatial Profile (Fit to Gaussian)[9]	
Near Field (<1m)	0.7
Far Field (∞)	0.95
Max Deviation from fitted Gaussian[10] (±%)	
Near Field (<1m)	40



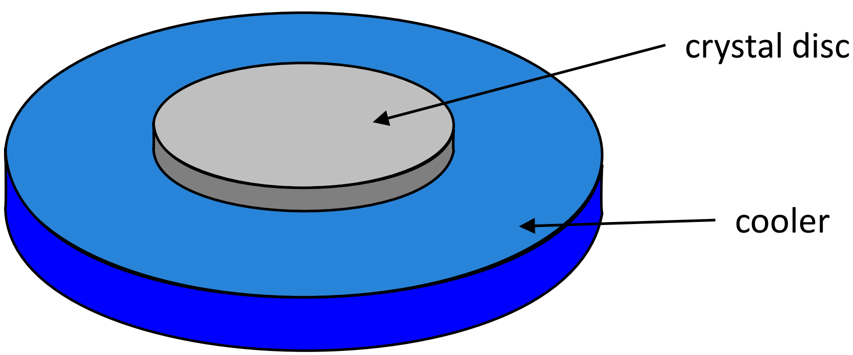
Powerlite DLS 2J Beam Quality - 2 J at 532 nm

heat management in the laser crystal

The limitation for the average power of a solid state laser comes from the heat deposited in the laser crystal. The scaling depends on dimensionality:

Bulk crystal – a cube. Scaling:

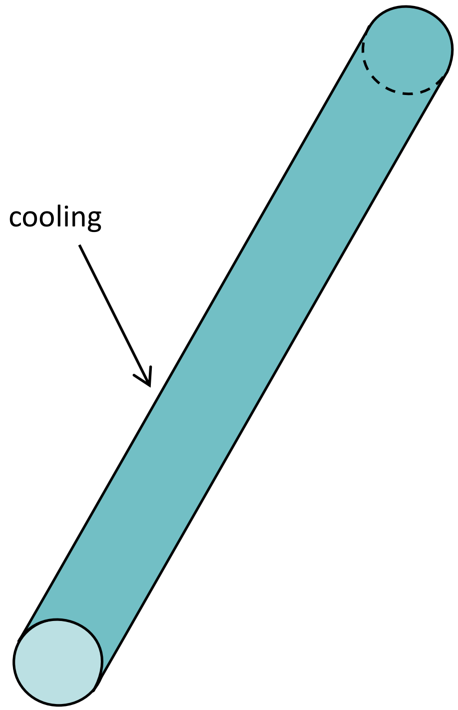
- thermal power $\propto L^3$
- heat removal proportional the crystal surface $\propto L^2$
- cooling efficiency $\propto {}^{1}/_{L}$



Flat (2-D) – a disc of constant thickness. Scaling:

- thermal power $\propto L^2$
- heat removal proportional the crystal face surface $\propto L^2$
- cooling efficiency does not depend on the area of the crystal surface

bulk – laser rod



Assume the crystal to be a long cylinder with length L >> $2r_0$= diameter

The heat is uniformly deposited in the whole volume of the crystal, heat is removed through the cylindrical surface of the crystal which is kept at temperature of the cooling liquid T_0

- thermal power density $Q = \frac{P_{th}}{\pi {r_0}^2 L}$, with P_{th} being the total power delivered to crystal as heat
- thermal conductivity λ_{th}

Let r be the distance from cylinder axis. Heat diffusion equation

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{Q}{\lambda_{th}} = 0$$

has the solution

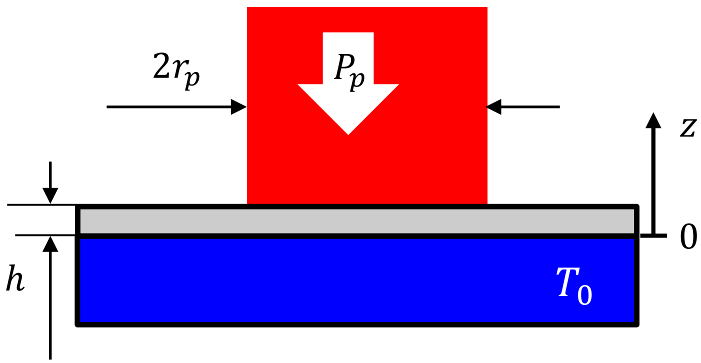
$$T(r) = T_0 + \frac{Q}{4\lambda_{th}}({r_0}^2 - r^2)$$

The maximum temperature difference is

$$T(0) - T(r_0) = \frac{Q{r_0}^2}{4\lambda_{th}} = \frac{P_{th}}{4\pi\lambda_{th}L}$$

The longer the rod the smaller is the temperature gradient. In the limit we have a fiber laser.

disc geometry



P_p - pump power
r_p - radius of the pump beam
η_a - efficiency of the pump absorption
η_h - efficiency of the heat production
I_{th} - thermal power per unit surface

$$I_{th} = \frac{P_{th}}{\pi {r_p}^2} = \frac{P_p \eta_a \eta_h}{\pi {r_p}^2}$$

Assume the crystal to be thin – its thickness h is much smaller than r_p. In this case the heat flow is in one direction only – towards the cooler. The corresponding heat diffusion equation gives the temperature distribution along the disc axis

$$T(z) = I_{th} R_{th,d} \left(\frac{z}{h} - \frac{1}{2} \frac{z^2}{h^2} \right)$$

$R_{th,d} = {}^{h}/_{\lambda_{th}}$ - thermal resistivity of the disc

The maximum temperature difference

$$T(h) - T(0) = \frac{1}{2} I_{th} R_{th,d} = \frac{P_{th} h}{2\pi {r_p}^2 \lambda_{th}}$$

$$\frac{P_{th}}{2\pi\lambda_{th}} \frac{1}{2L} \leftrightarrow \frac{P_{th}}{2\pi\lambda_{th}} \frac{h}{{r_p}^2}$$

rod disc

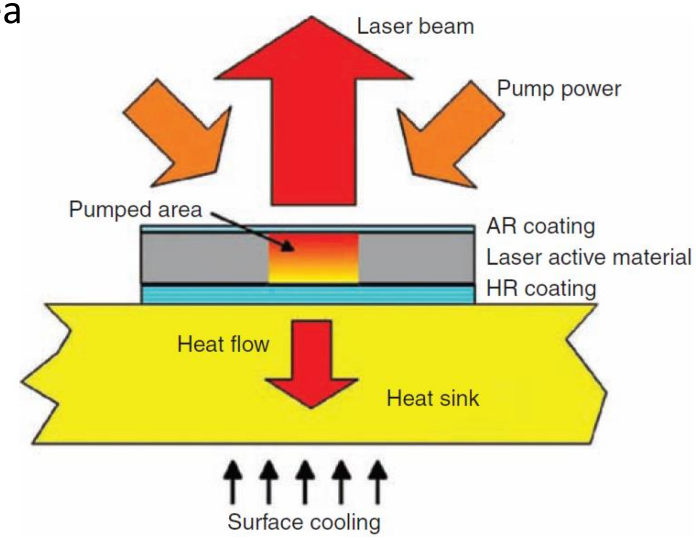
$$\frac{1}{2L} \leftrightarrow \frac{h}{{r_p}^2}$$

typical numbers:
$L = 10cm, \quad h = -0.01cm, r_p = 0{,}5cm$

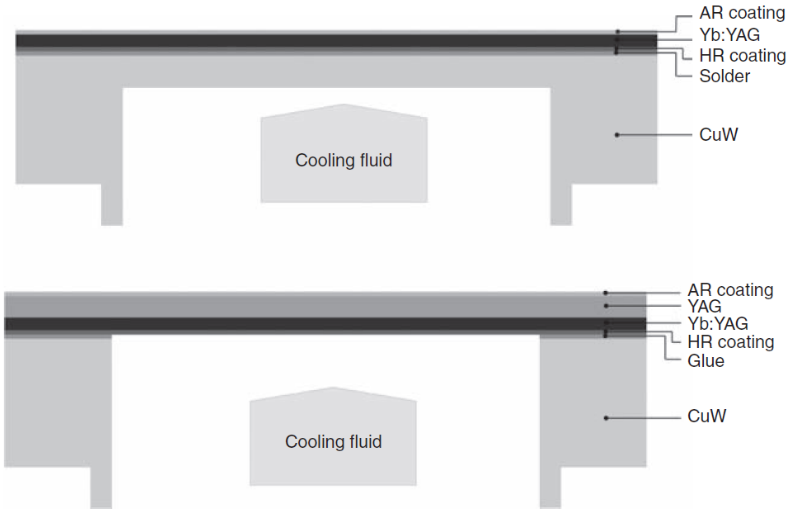
$$\frac{1}{10} \leftrightarrow \frac{1}{25}$$

thin disc solid state lasers

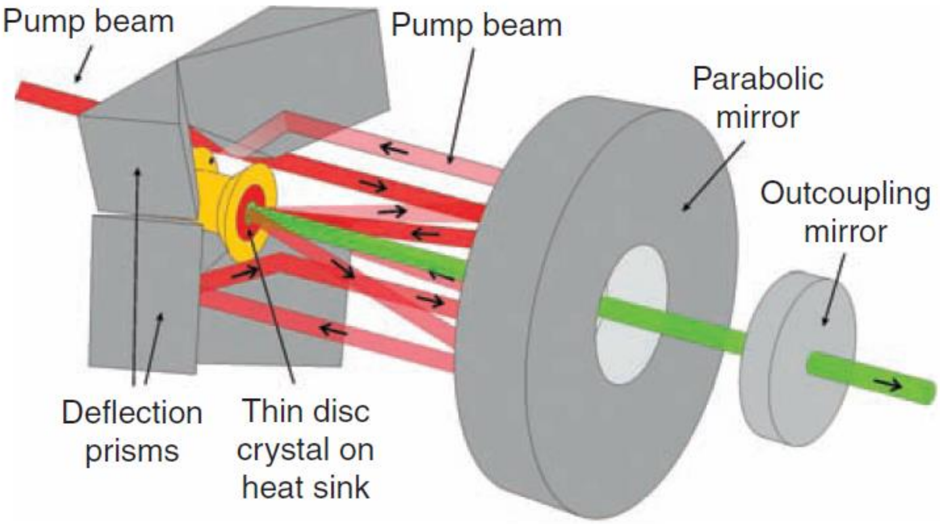
idea



technical realization



multi-pass pump setup

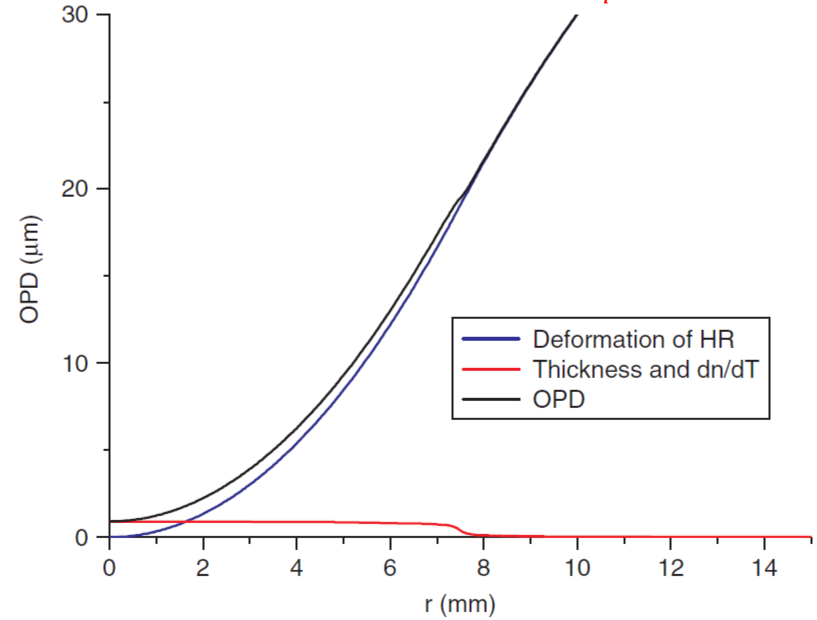


thin disc solid state lasers, 2

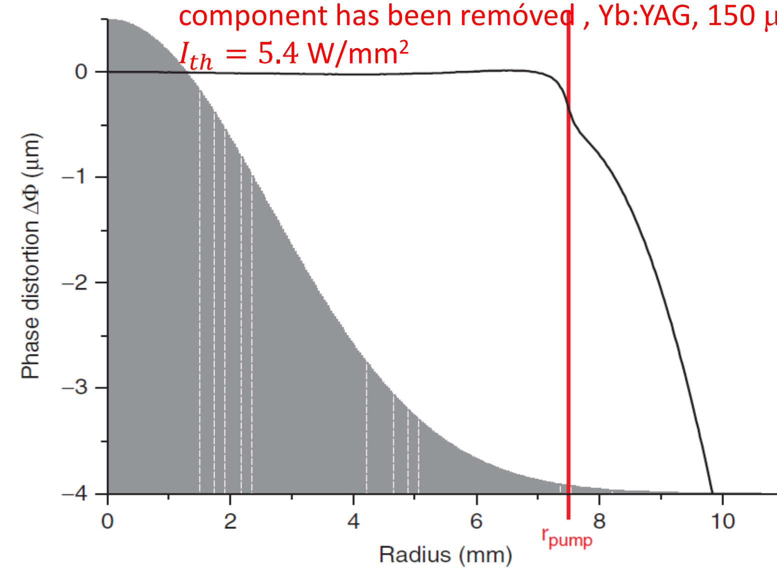
materiały

Host Material	
YAG	Yb^{3+}, $Nd^{(3+)}$ 9–11, $Tm^{(3+)}$ 12,13, $Ho^{(3+)}$ 14
YVO_4	$Yb^{(3+)}$ 15–17, $Nd^{(3+)}$ 18–21
Sc_2O_3	$Yb^{(3+)}$ 22
Lu_2O_3	$Yb^{(3+)}$ 22,23
$KY(WO_4)_2$	$Yb^{(3+)}$ 22
$KGd(WO_4)_2$	$Yb^{(3+)}$ 22
$NaGd(WO_4)_2$	$Yb^{(3+)}$ 15,17
$LaSc_3(BO_3)_4$	$Yb^{(3+)}$ 24
$Ca_4YO(BO_3)_3$	$Yb^{(3+)}$ 25
$GdVO_4$	$Nd^{(3+)}$ 21
ZnSe	$Cr^{(2+)}$ 26

Yb:YAG, 150 μm, $I_{th} = 5.4$ W/mm² ($I_p = 60$ W/mm²)



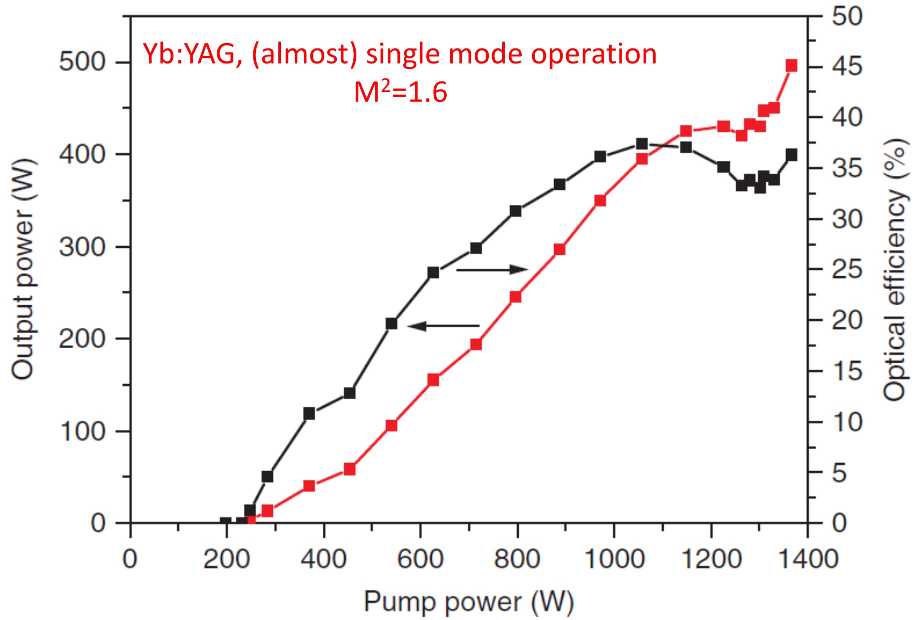
Phase front deformation after the sperical component has been remóved , Yb:YAG, 150 μm, $I_{th} = 5.4$ W/mm²

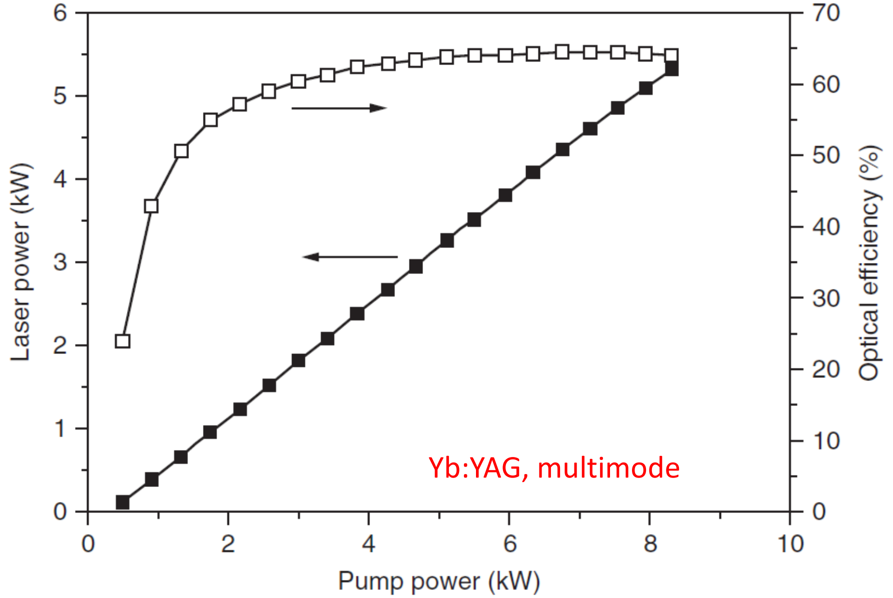


Important parameters:

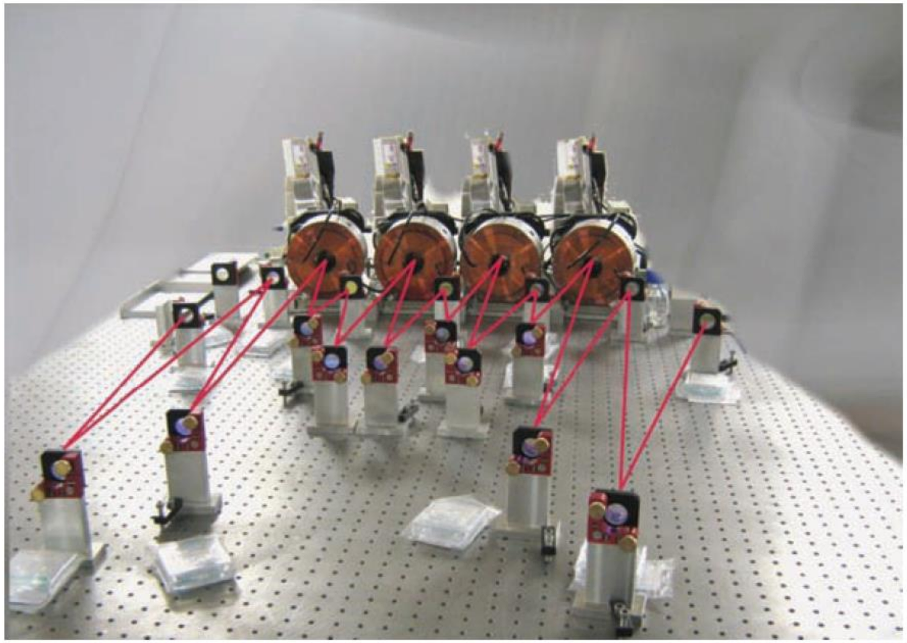
thermal conductivity , $\lambda_{th} = 6$ Wm⁻¹K⁻¹ (for YAG)
absorption coefficient
quantum defect: $\eta_{th} = 1 - {}^{\lambda_p}/_{\lambda_l}$ =0.087 (for Yb:YAG)

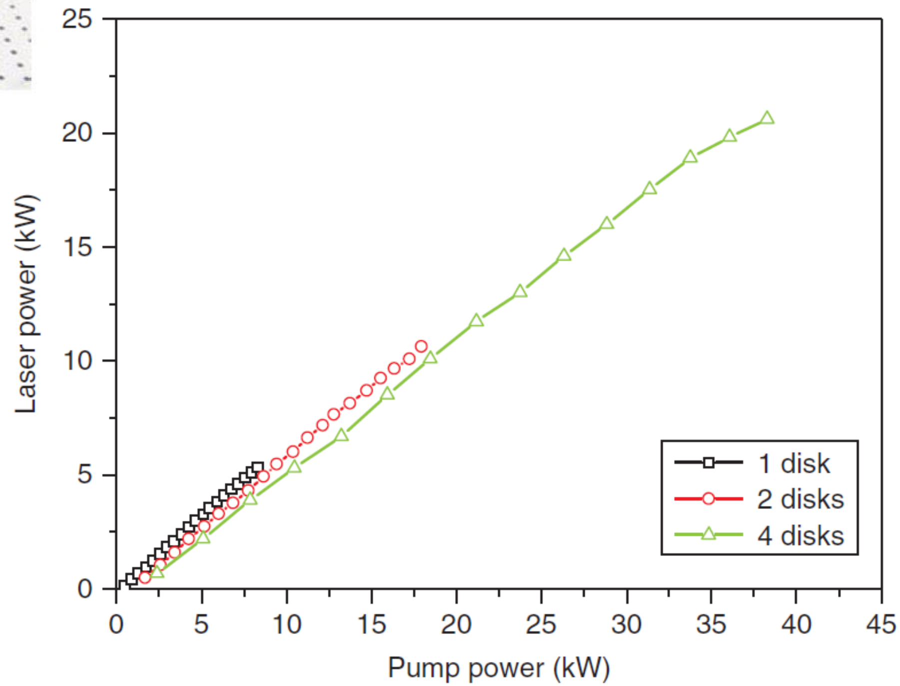
thin disc lasers, some parameters



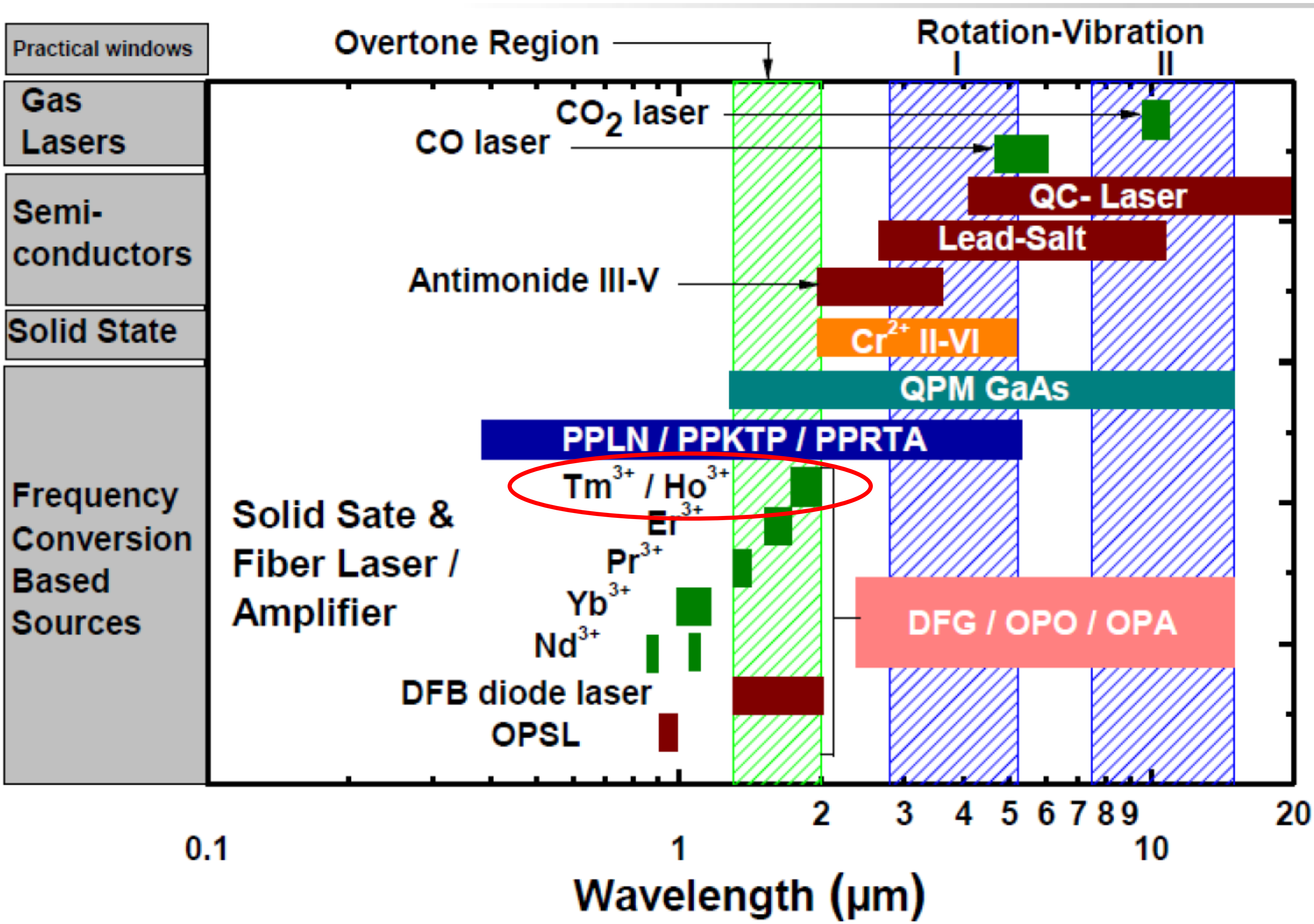


multi-disc lasers, parameters





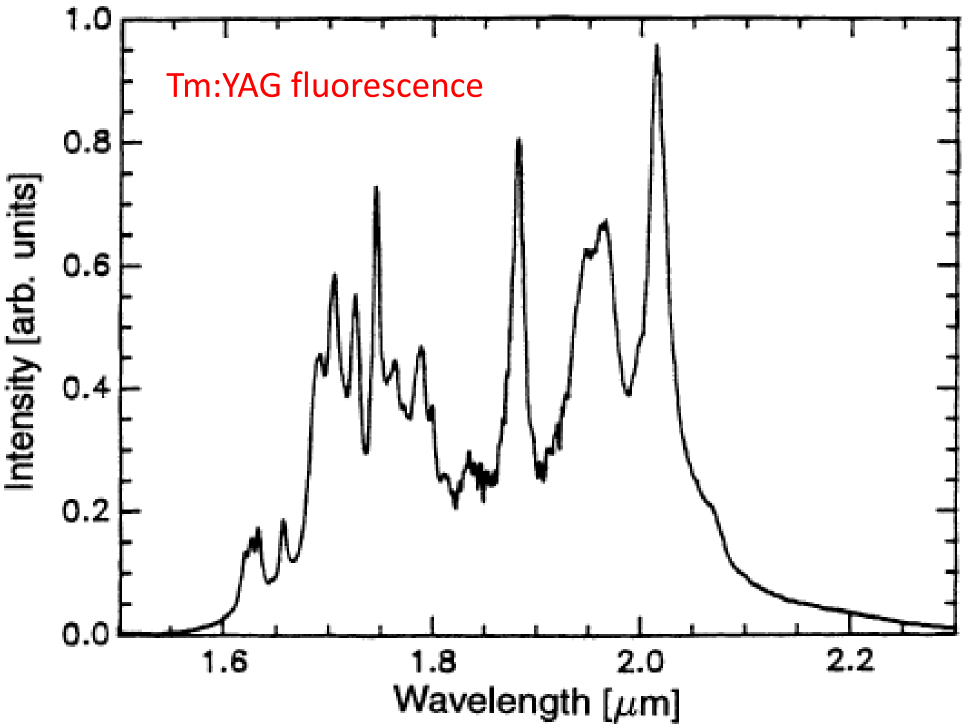
MID IR - eye safe region lasers



MID IR lasers, 2

Tm:YAG

Pump wavelength	780–785 nm
Peak laser wavelength	2.02 μm
Effective cross section at 25°C	2×10^{-21} cm^2
Fluorescence lifetime	10 ms
Tunability	1.87–2.16μm



MID IR lasers, 3

Table 11 Important data on Ho^{3+}-doped laser hosts (BYF: BaY_2F_8). Some data are taken from [7, 11, 64, 180, 181]

Host crystal	YAG	YALO	YLF	BYF
Symmetry	cubic	orthorhombic	tetragonal	monoclinic
$^5I_7$ levels [cm^{-1}]	5229, 5232, 5243, 5250, 5303, 5312, 5320, 5341, 5352, 5375, 5395, 5404, 5418, 5455, 5485	5186, 5187, 5222, 5253, 5255, 5264, 5266, 5268, 5280, 5288, 5318, 5326, 5337, 5346, 5357	5153, 5157, 5157, 5164, 5164, 5185, 5185, 5207, 5229, 5229, 5233, 5291, 5293, 5293, 5293	5173, 5177, 5189, 5191, 5197, 5220, 5220, 5220, 5220, 5228, 5256, 5269, 5273, 5276, 5358
$f_{u,(i)}$	0.105 (1), 0.096 (3)	0.100 (0)	0.087 (0)	0.084 (1)
τ_f [ms]	7.8	8.1	16.1	17.9
$^5I_8$ levels [cm^{-1}]	0, 4, 41, 51, 141, 144, 150, 162, 398, 418, 448, 457, 498, 506, 520, 531, 535	0, 6, 37, 48, 58, 71, 100, 126, 137, 193, 211, 222, 289, 327, 425, 474, 499	0, 0, 7, 23, 48, 56, 72, 72, 217, 270, 276, 276, 283, 290, 303, 303, 315	0, 20, 37, 39, 54, 58, 89, 120, 200, 200, 239, 276, 310, 324, 352, 382, 399
$f_{g,(i)}$	0.018 (10), 0.012 (16)	0.012 (15)	0.025 (14)	0.025 (13)
λ_s [nm]	2090, 2121	2122	2062	2060
$\sigma_e(\lambda_s)$ [10^{-20} cm^2]	1.2, 0.55	0.82	1.9 ($E \parallel c$)	1.18 ($E \parallel c$)
$\frac{\sigma_e(\lambda_s)}{\sigma_a(\lambda_s)}$	5.81, 8.13	8.39	3.44	3.42
I_{sat}^s [kW cm^{-2}]	0.866, 1.94	1.26	0.244	0.353
λ_p [nm]	1907, 2017	1976	1948	1933
$\sigma_{a,p}(\lambda_p)$ [10^{-20} cm^2]	1.2, 0.15	0.9	1.2 ($E \parallel c$)	0.7 ($E \parallel c$)
$\frac{\sigma_{e,p}(\lambda_p)}{\sigma_{a,p}(\lambda_p)}$	0.64, 2.53	1.58	0.88	0.74
I_{sat}^p [kW cm^{-2}]	0.949, 0.898 (2090 nm) 2.16, 2.04 (2121 nm)	1.35	0.258	0.376
E_P^{max} [cm^{-1}]	700	550	400	415

MID IR lasers, an example of design