Advanced Vitreous State – The Physical Properties of Glass

Active Optical Properties of Glass

Lecture 1: Fluorescence, Amplifiers and Lasers

Denise Krol
Department of Applied Science
University of California, Davis
Davis, CA 95616
dmkrol@ucdavis.edu

Active Optical Properties of Glass

1. Light emission ➡ Optical amplification and lasing

   (fluorescence, luminescence)

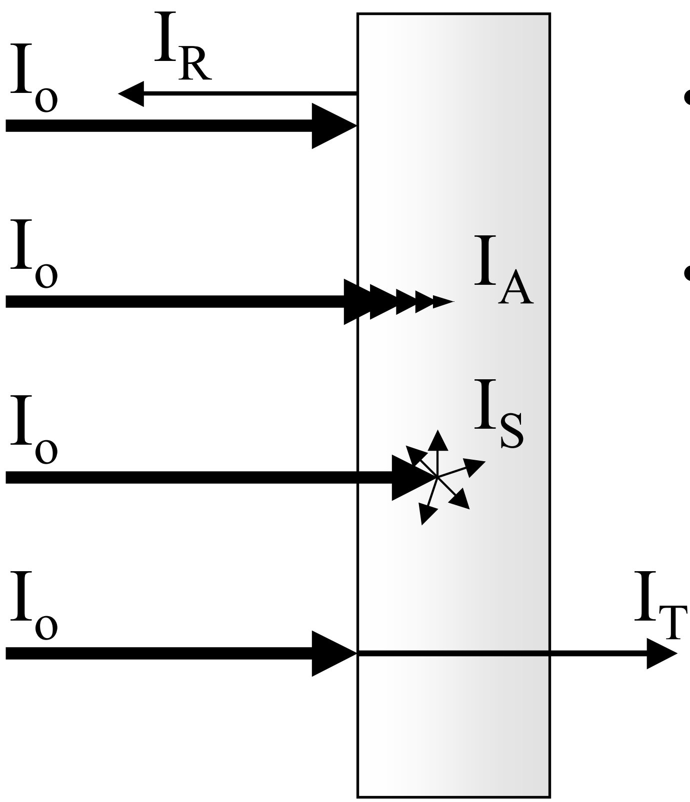
   Optical transitions, spontaneous emission, lifetime, line broadening, stimulated emission, population inversion, gain, amplification and lasing, laser materials, role of glass

2. Nonlinear Optical Properties

   Fundamentals: nonlinear polarization, 2nd-order nonlinearities, 3rd-order nonlinearities
   Applications: thermal poling, nonlinear index, pulse broadening, stimulated Raman effect, multiphoton ionization

Optical properties of materials (Lucas, lecture 16)

- Four things can happen when light proceeds into a solid.

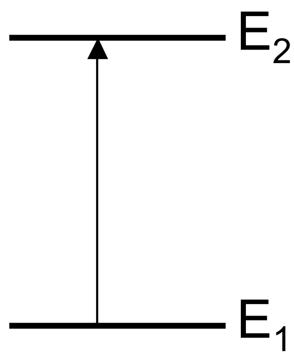


- Part of the light can be reflected by the surface of the solid. Reflection
- Part of the light can be absorbed by coupling into the solid. Absorption
- Part of the light can be scattered by the atoms and defects in the solid. Scattering
- Part of the light can be transmitted through the solid. Transmission

- Therefore, for an incident beam of intensity I_o entering the solid:

$$\mathbf{I_o = I_R + I_T + I_A + I_S}$$

Optical transitions: absorption and emission



An atom/ion in a material, such as glass, can absorb light,

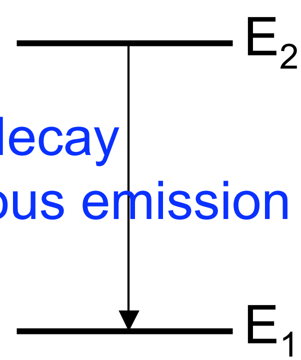
$$h\nu = E_2 - E_1$$

ν is the frequency of light (photon)

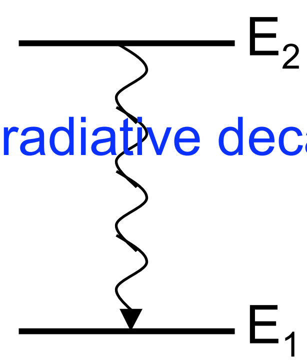
After absorption, the material does not stay in the excited state indefinitely, but it will go back to the ground state either by

emitting light   or   giving off heat

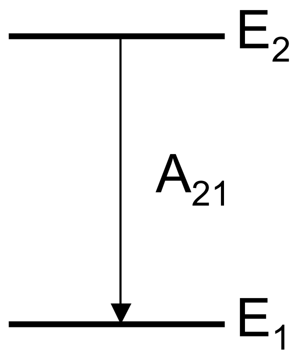
radiative decay
spontaneous emission



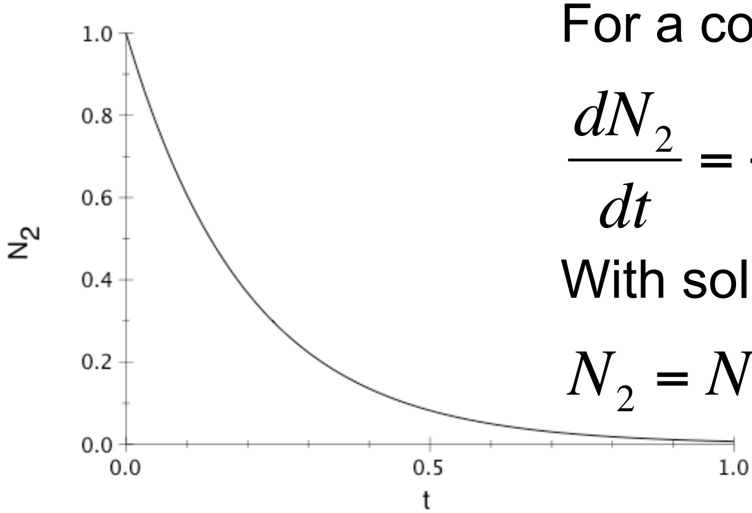
non-radiative decay



Spontaneous emission and lifetime



There is a certain probability (A_{21}) for the atom to decay radiatively



For a collection of N_2 atoms in the excited state:

$$\frac{dN_2}{dt} = -A_{21}N_2$$

With solution:

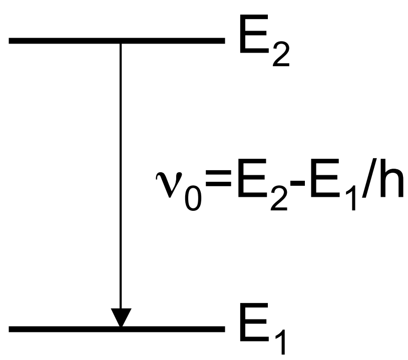
$$N_2 = N_{20}e^{-A_{21}t} = N_{20}e^{-t/\tau}$$

τ is the lifetime

Including non-radiative decay:

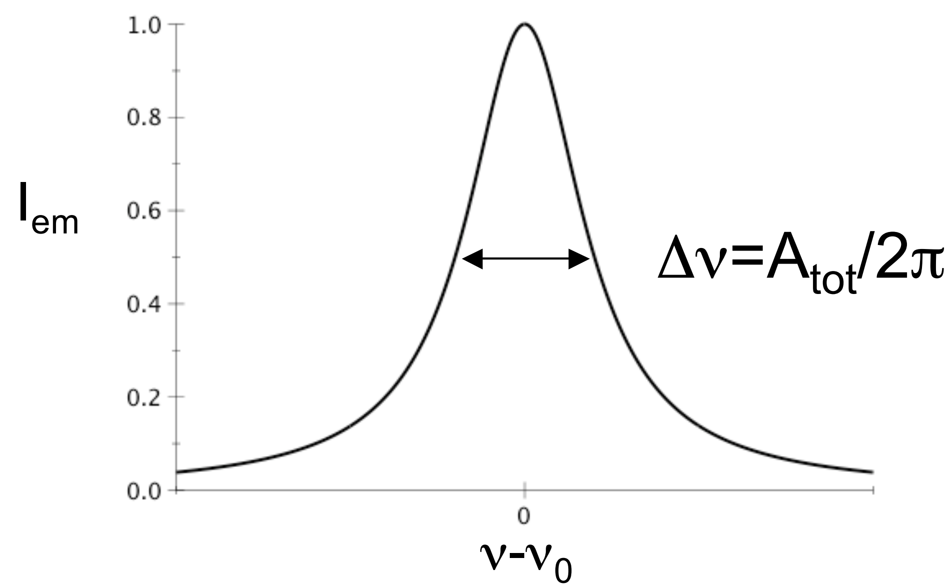
$A_{tot} = A_{21} + A_{nr} \longrightarrow \tau = 1/A_{tot}$

Line broadening: homogeneous



The finite lifetime of the excited state leads to a broadening of the emission linewidth:

$$I(\nu) = I_0 \frac{A_{tot}/4\pi^2}{(\nu-\nu_0)^2 + (A_{tot}/4\pi)^2}$$



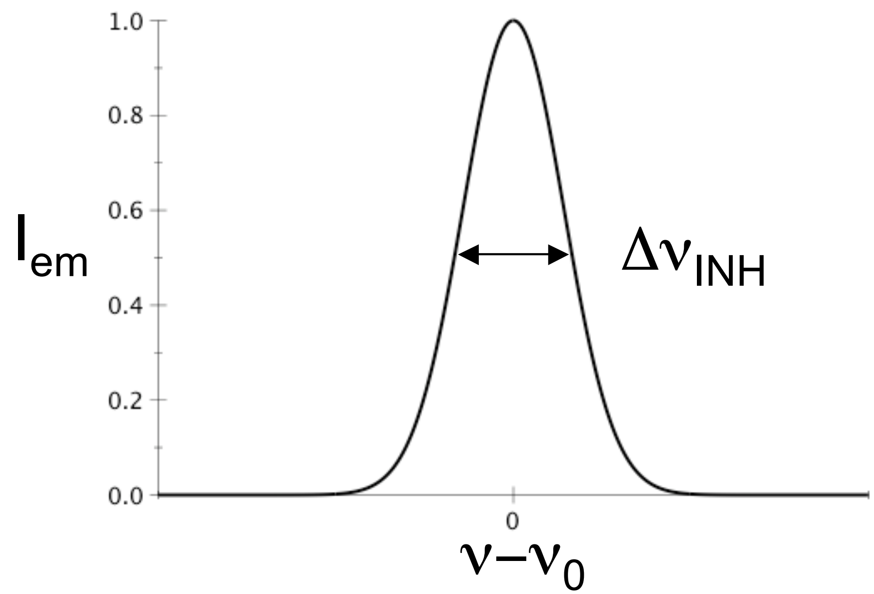
The lineshape is Lorentzian and the same for all atoms

homogeneous broadening

Line broadening: inhomogeneous

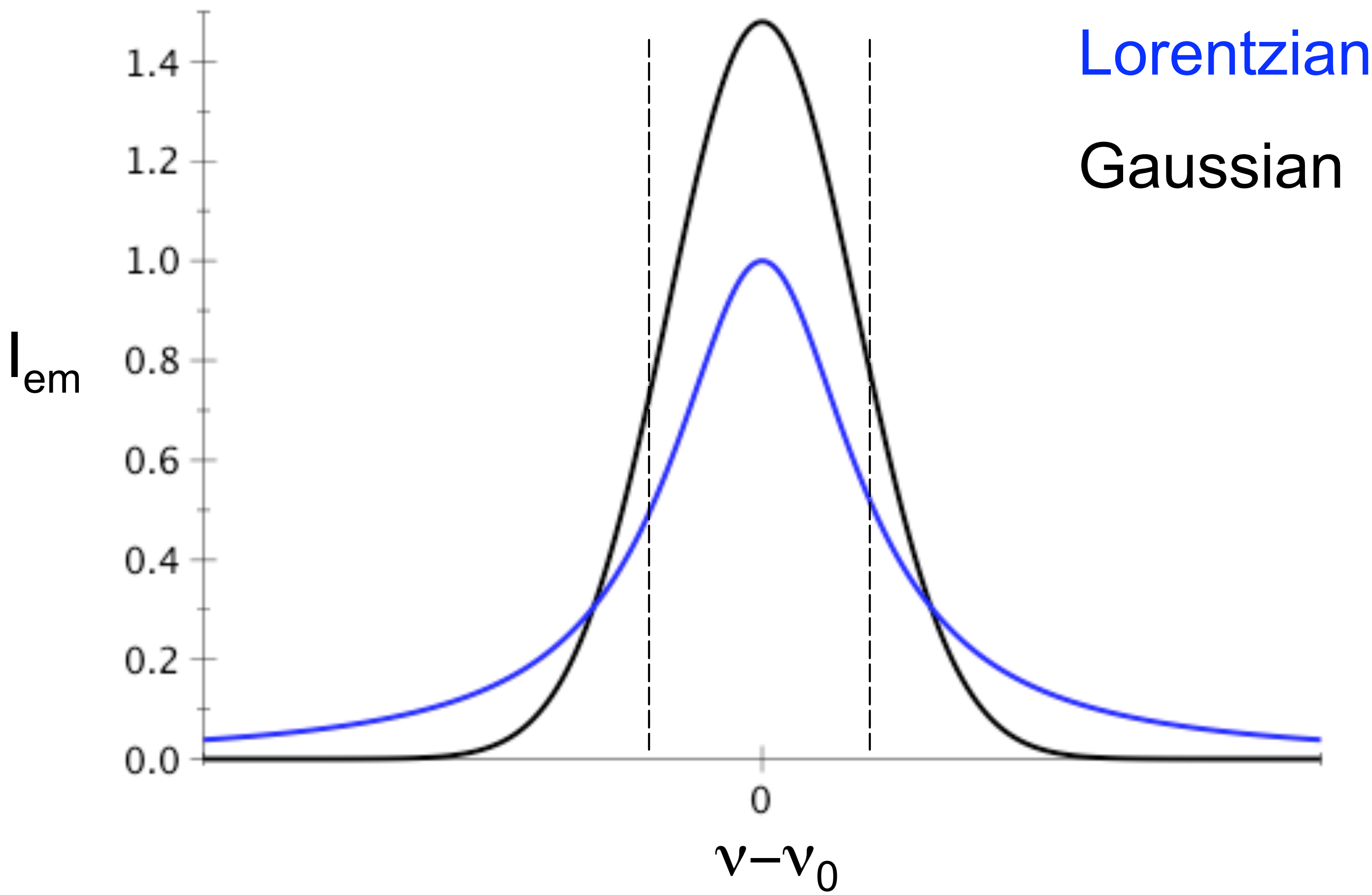
There is also a broadening that results from the fact that not all atoms have the same surroundings (glass!) ⟶ different atoms have slightly different transition frequencies
The spread in frequencies is characterized by $\Delta\nu_{INH}$

$$I(\nu) = I_0 \frac{2(\ln 2)^{1/2}}{\pi^{1/2}\Delta\nu_{INH}} \exp\left\{-\left[\frac{4(\ln 2)(\nu-\nu_0)^2}{(\Delta\nu_{INH})^2}\right]\right\}$$



The resulting lineshape is Gaussian inhomogeneous broadening

Line broadening: homogeneous vs inhomogeneous



curves have same area and half-width

Glass: strong inhomogeneous broadening

In general, one or the other line broadening mechanism can dominate
In glasses -due to their disorder- inhomogeneous broadening almost always dominates

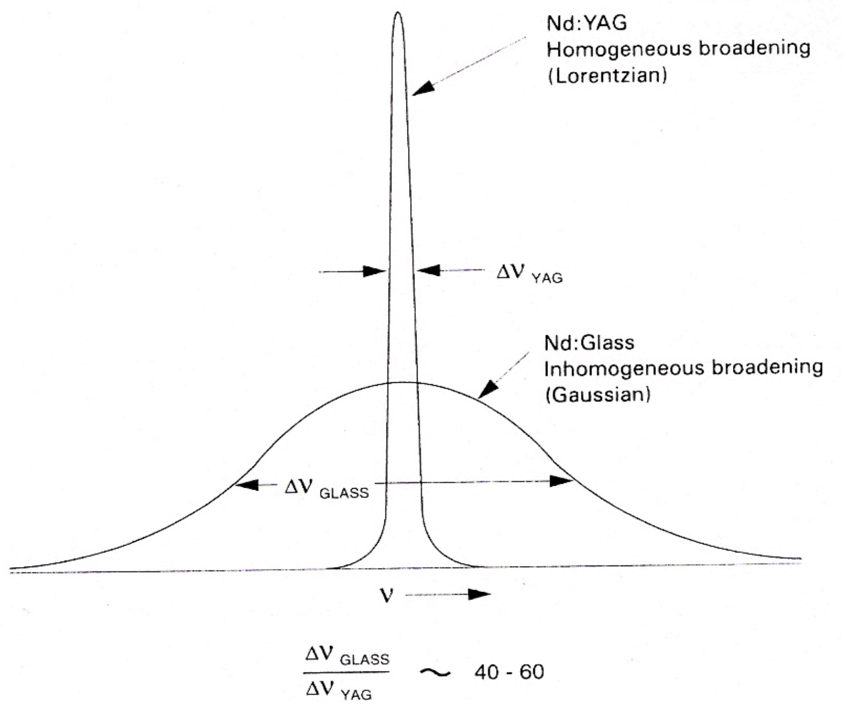
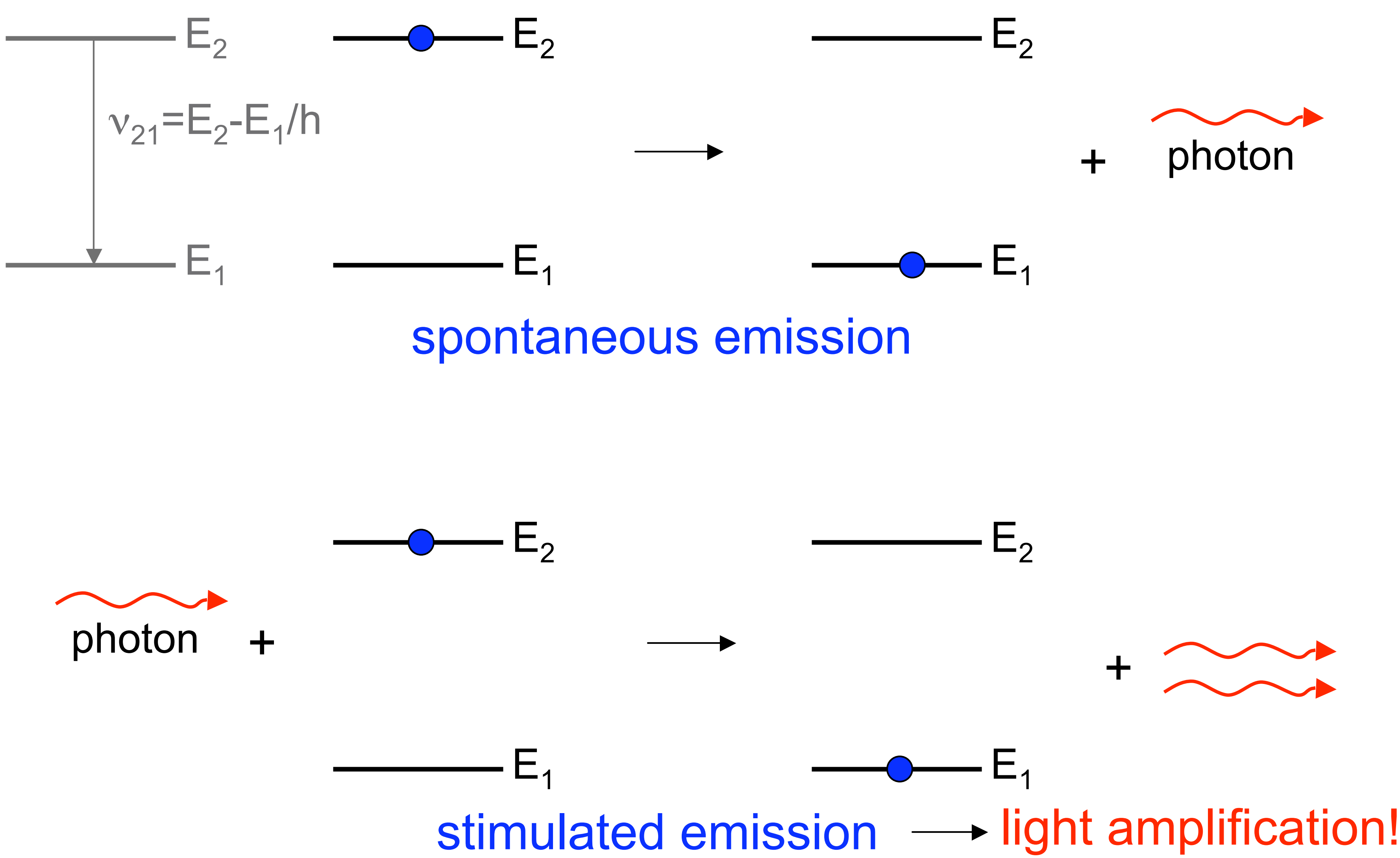


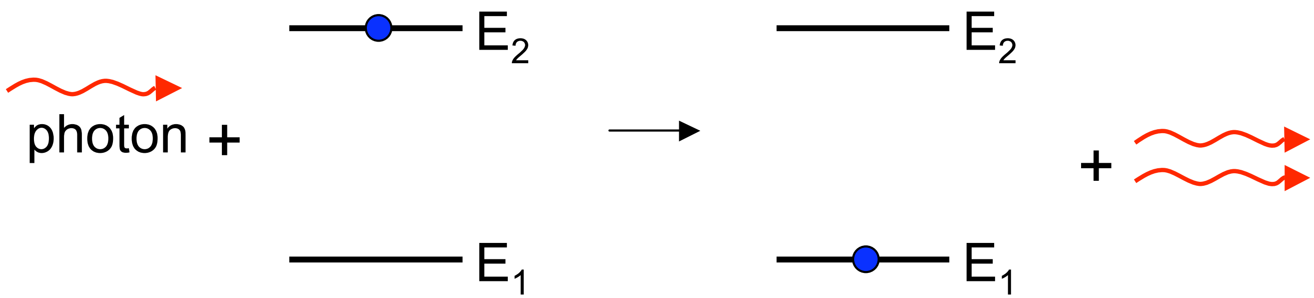
Figure 4-11 Relative emission linewidths of a radiating Nd ion doped into either a YAG crystal or a glass material

From W.T. Silfvast, Laser Fundamentals, 2nd ed., Cambridge (2004)

Spontaneous vs stimulated emission

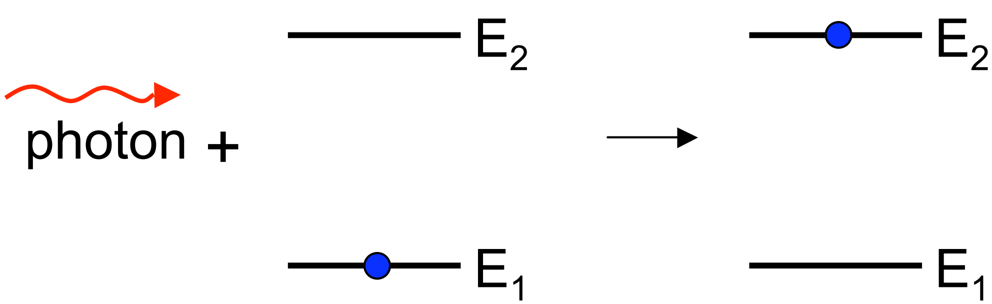


Stimulated emission vs absorption



stimulated emission

But we also have



absorption

To have net amplification of light (gain) we need $N_2 > N_1$

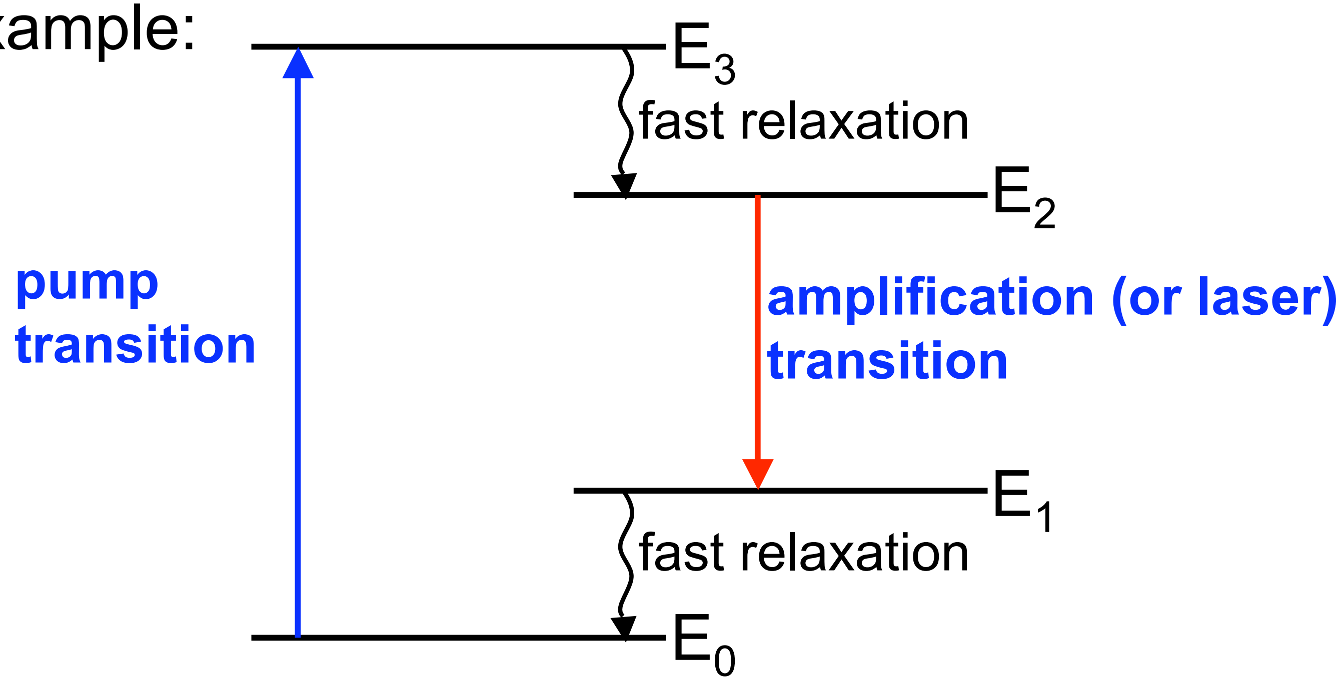
We need population inversion

Population Inversion

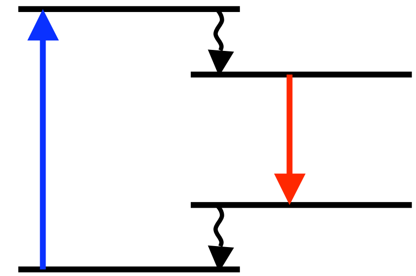
If there are only 2 levels inversion is not possible

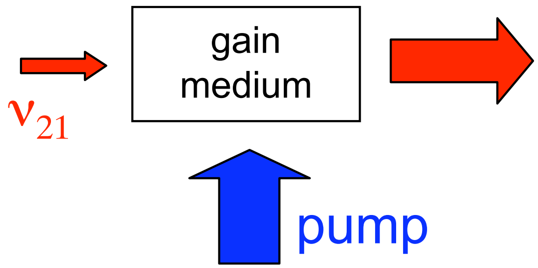
But if we have >3 levels inversion can be obtained

Example:



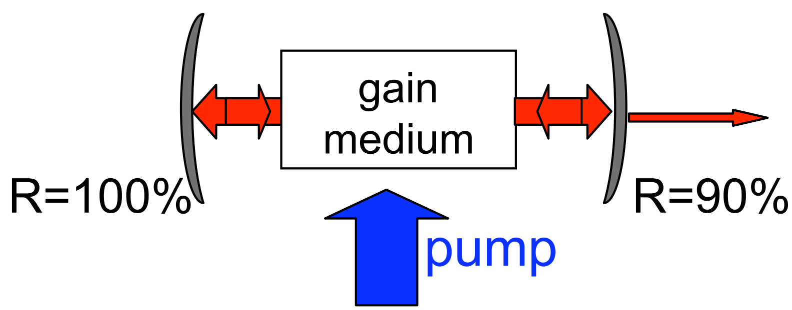
Optical Amplification and Lasing





amplifier

Because of stimulated process, amplified light has direction and phase of incoming signal

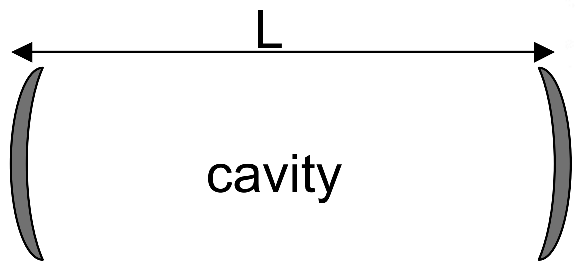


laser =
amplifier + optical cavity

laser light has the following properties:

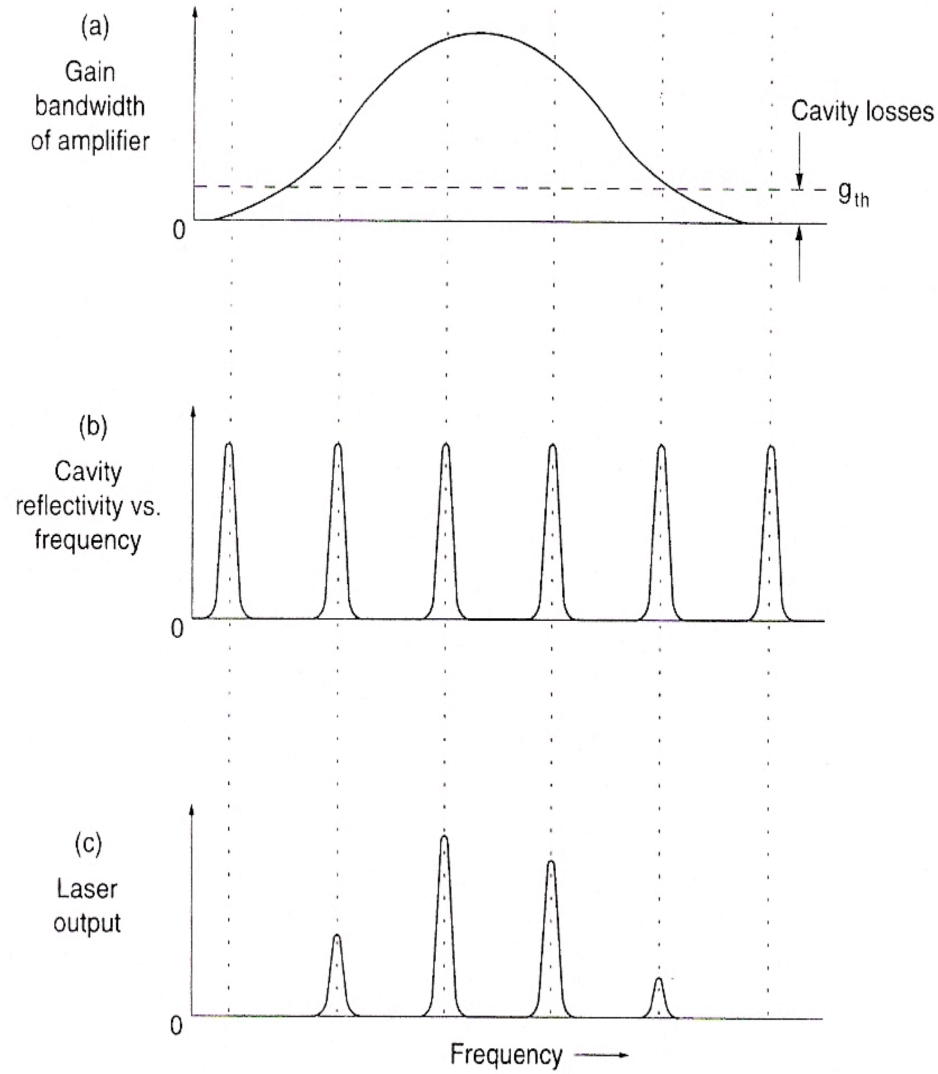
- highly directional
- highly monochromatic
- highly coherent

Optical cavity modes



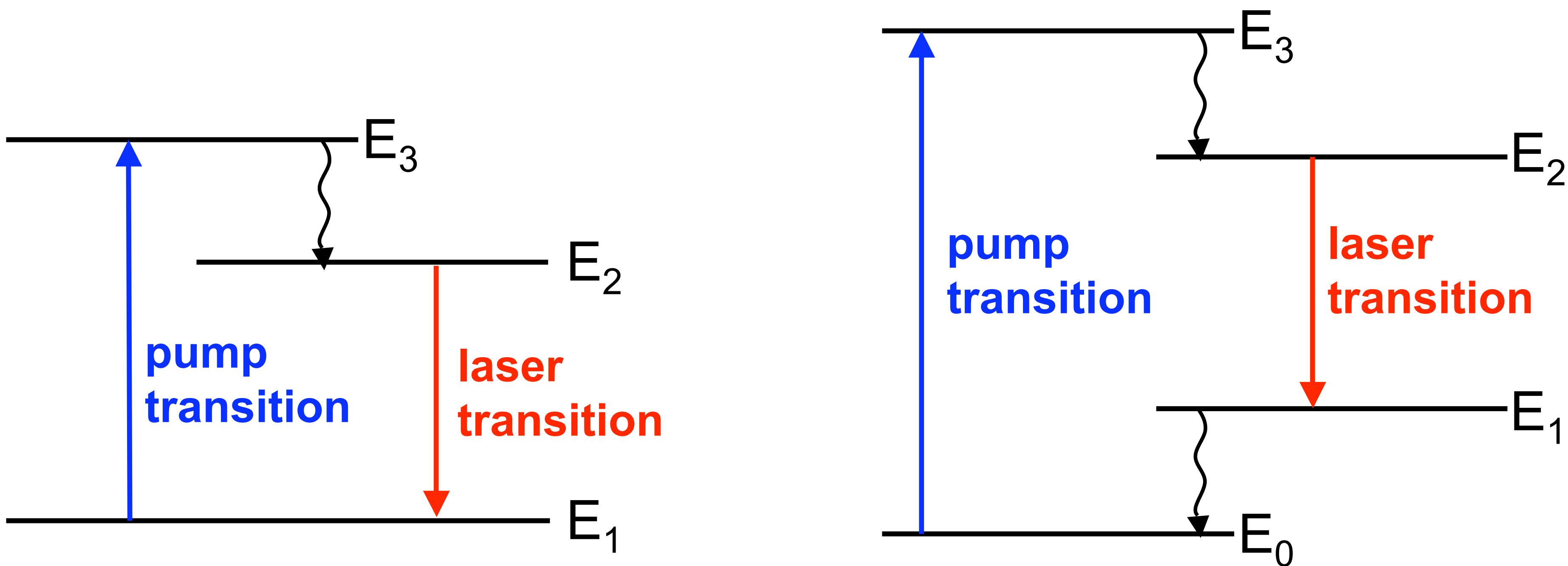
axial mode frequencies ν = nc/2L

axial mode separation $\Delta\nu$=c/2L



F
la
g
ai
re
la

3-Level vs 4-Level Laser System



3-level system
example : Er^{3+}

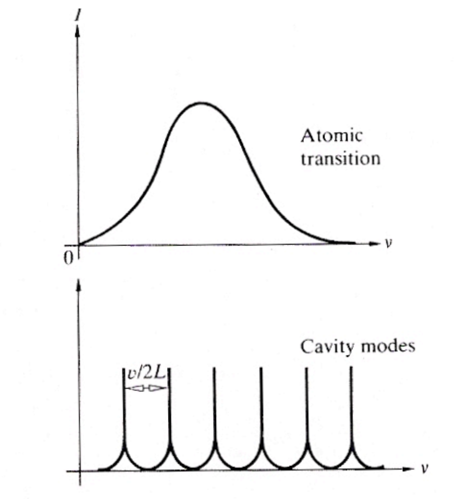
4-level system
example : Nd^{3+}

In 3-level system more than 50% of level 1 needs to be pumped, so it is harder to obtain inversion:
Pump and laser transition share a level

Some simple laser equations

note: cw lasers!

$$e^{2g_{th}L} = \frac{1}{R^2}$$ **gain =loss and ν = nc/2L**



(b)

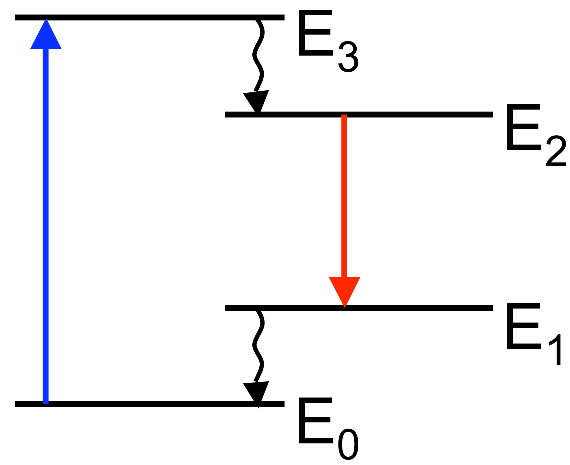
$g_{th} = \sigma\Delta N_{th}$ where σ is the emission cross-section (m^2).
R = mirror reflectivity

The lasing threshold is achieved when the pump rate (proportional to pump power) is high enough to obtain ΔN_{th}.
If the pump rate is increased further the steady state laser intensity (power/area), I_{ss}, grows according to

$$I_{ss} = (P/P_{th} - 1)I_{sat}$$

Here P is the pump power, P_{th} the pump power needed to reach threshold and I_{sat} the saturation intensity (a fixed parameters for a given laser transition)

What makes a good laser transition/material?



For cw operation:

- Good pumping efficiency
- Purely radiative lasing transition
- Small difference between pump and laser wavelength
- Fast relaxation from 3 ->2 and 1->0

Other important materials properties:
- Thermal conductivity
- Optical quality
- Mechanical properties

Solid-state laser materials and glass

Most solid state laser materials fall in one of 2 categories:

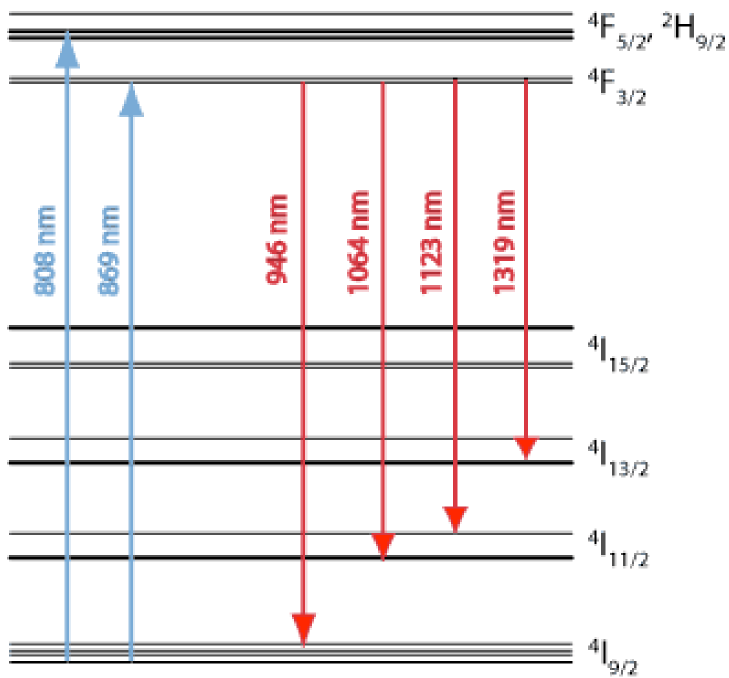
1. Dielectric materials (host material)doped with active ions: Nd^{3+}:YAG, Cr^{3+}:Al_2O_3
2. Semiconductor materials: GaAs, GaN

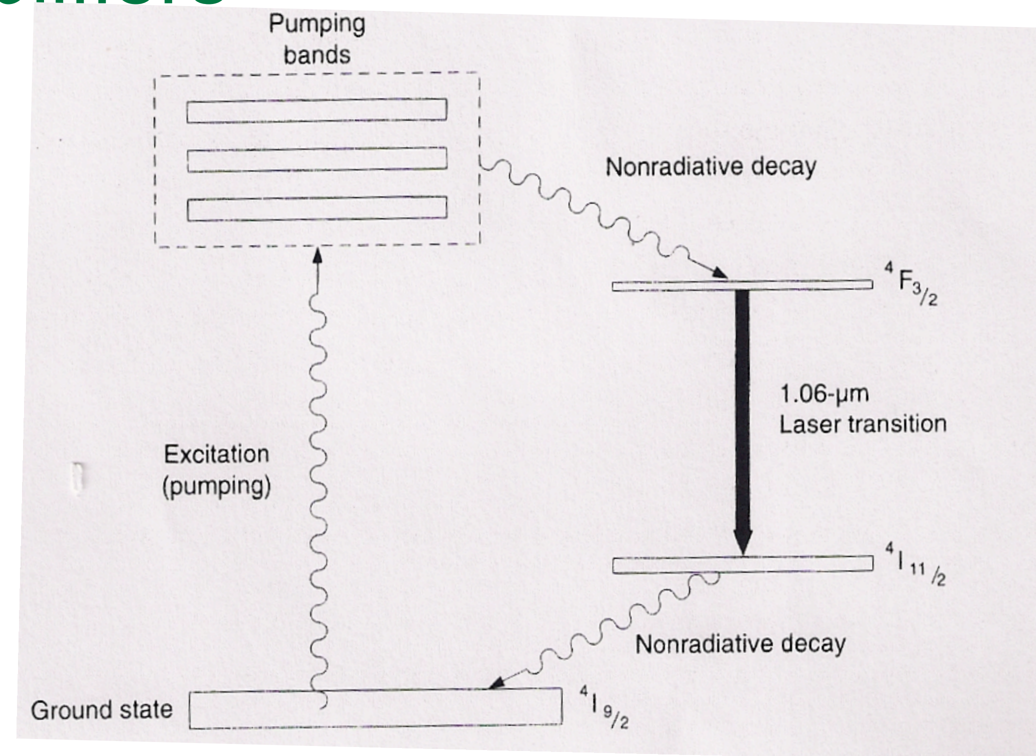
transition-metal ions (d-shell, broad transitions)	rare-earth ions (f-shell, narrow transitions)
Cr^{3+}	Nd^{3+}
Ti^{3+}	Er^{3+}
	Yb^{3+}

Host material influences emission and laser characteristics

Glass is used as a host material

Nd-doped glass amplifiers





Nd^{3+} energy level diagram

corresponding 4-level laser diagram for 1064 nm transition

crystals: narrow lines, better thermal conductivity → lasers

glass: uniform & large pieces, broader lines, lower thermal conductivity → amplifiers

Nd-doped glass amplifiers

Phosphate glass preferred

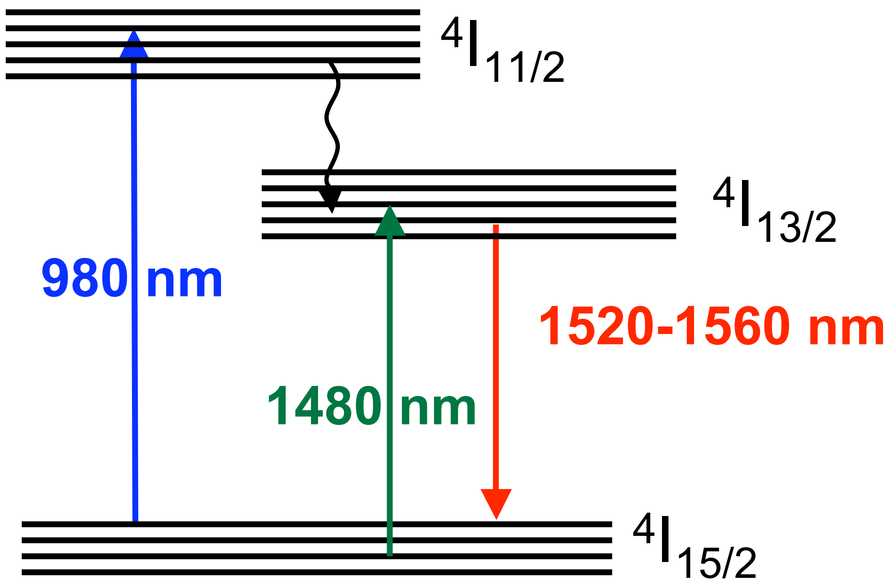
Table 2.7. Physical and optical properties of Nd-doped glasses

Glass Type / Spectroscopic Properties	$Q-246$ Silicate (Kigre)	$Q-88$ Phosphate (Kigre)	$LHG-5$ Phosphate (Hoya)	$LHG-8$ Phosphate (Hoya)	$LG-670$ Silicate (Schott)	$LG-760$ Phosphate (Schott)
Peak Wavelength [nm]	1062	1054	1054	1054	1061	1054
⇨ Cross Section [$\times 10^{20}$ cm]	2.9	4.0	4.1	4.2	2.7	4.3
Fluorescent Lifetime [μs]	340	330	290	315	330	330
Linewidth FWHM [nm]	27.7	21.9	18.6	20.1	27.8	19.5
Density [gm/cc]	2.55	2.71	2.68	2.83	2.54	2.60
Index of Refraction [Nd]	1.568	1.545	1.539	1.528	1.561	1.503
⇨ Nonlinear Index n_2 [10^{-13} esu]	1.4	1.1	1.28	1.13	1.41	1.04
dn/dt (20°–40° C [10^{-6}/° C]	2.9	−0.5	8.6	−5.3	2.9	−6.8
Thermal Coefficient of Optical Path (20°–40° C) [10^{-6}/° C]	+8.0	+2.7	+4.6	+0.6	8.0	–
Transformation Point [° C]	518	367	455	485	468	–
Thermal Expansion coeff. (20°–40°) [10^{-7}/° C]	90	104	86	127	92.6	138
Thermal Conductivity [w/m]	1.30	0.84	1.19	–	1.35	0.67
Specific Heat [J/g • K]	0.93	0.81	0.71	0.75	0.92	0.57
Knoop Hardness	600	418	497	321	497	–
Young's Modulus [kg/mm^2]	8570	7123	6910	5109	6249	–
Poisson's Ratio	0.24	0.24	0.237	0.258	0.24	0.27

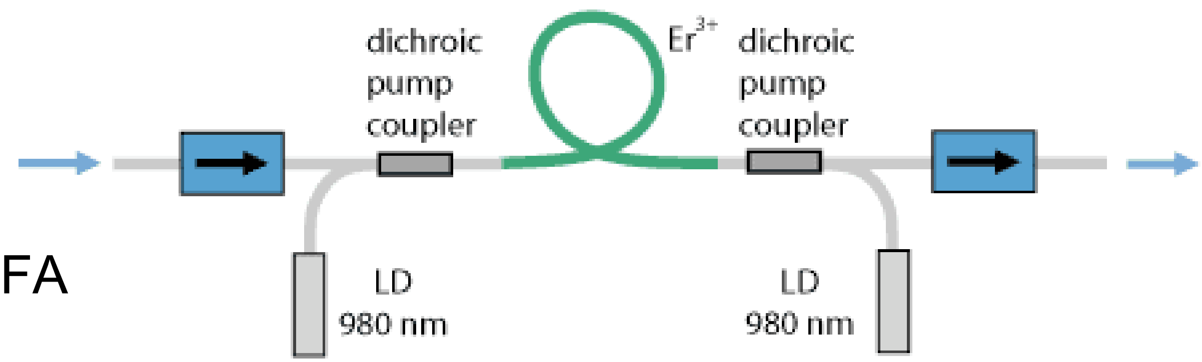
From W. Koechner, Solid State Laser Engineering

Erbium Doped Fiber Amplifier: EDFA

Glass fibers: long interaction lengths, compact and robust

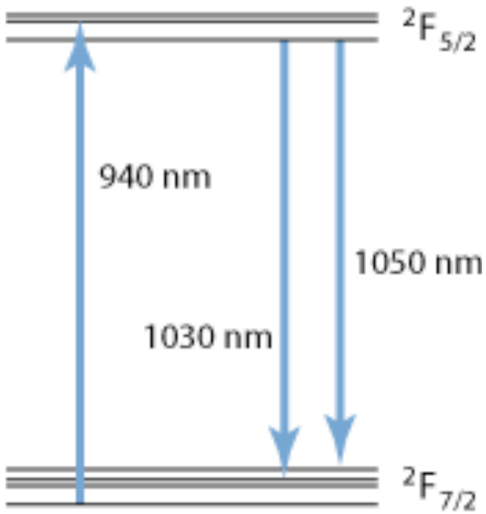


Energy levels of Er^{3+}
Pumping bands @ 980 or 1480 nm

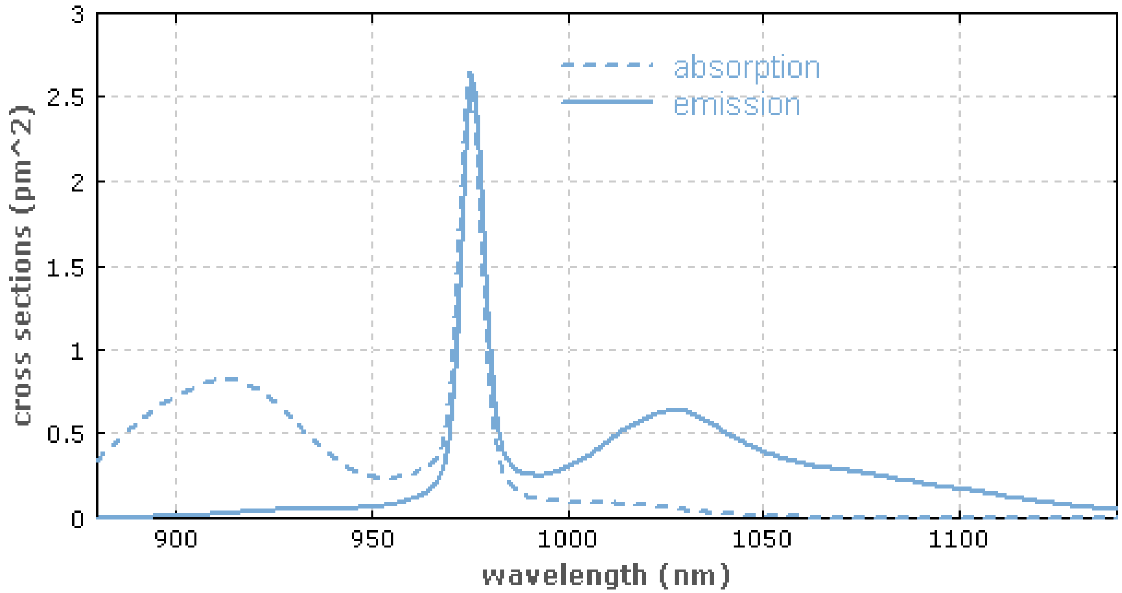


Schematic diagram of EDFA

Yb: Glass Fiber Laser



Quasi 3-level laser



Absorption and emission cross sections of ytterbium-doped germanosilicate glass, as used in the cores of ytterbium-doped fibers. (Data from spectroscopic measurements by R. Paschotta)

Very small difference between pumping and lasing wavelengths leads to minimal heating

Only 2 levels: no excited state absorption

Very high powers can be achieved: 50 kW!! Diode pumping

Fairly large bandwidth: $\Delta\nu \sim 1/\Delta\tau$ -> short pulse operation