Rare Earth Lasers & Amplifiers

The rare earth elements: atomic numbers 57-76

Nd(60) Er(68)

$^{2S+1}L_J$ $L=\overset{0}{S},P,\overset{2}{D},\overset{3}{F},\overset{4}{G},\overset{5}{H},\overset{6}{I}$

L= orbital momentum

J = total momentum

S = spin

Nd: YAG Lasers

doping: neodymium

1% Nd^{3+}

(3 electrons are bounded to the neighbor atoms)

$Y^{3+} \rightarrow Nd^{3+}$

host: yttrium aluminum garnet (YAG)

YAG – optically isotropic cubic crystal

$Y_3Al_5O_{12}$

lasing $\lambda = 1.064\mu m$

$^4F_{3/2} \rightarrow {}^4I_{11/2}$

four level laser:

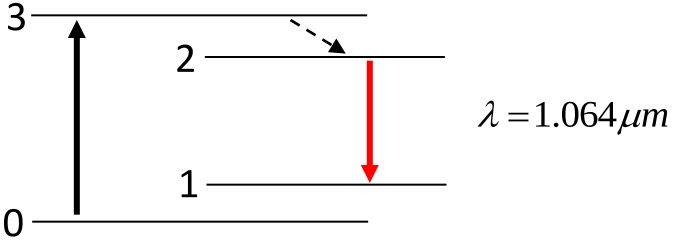
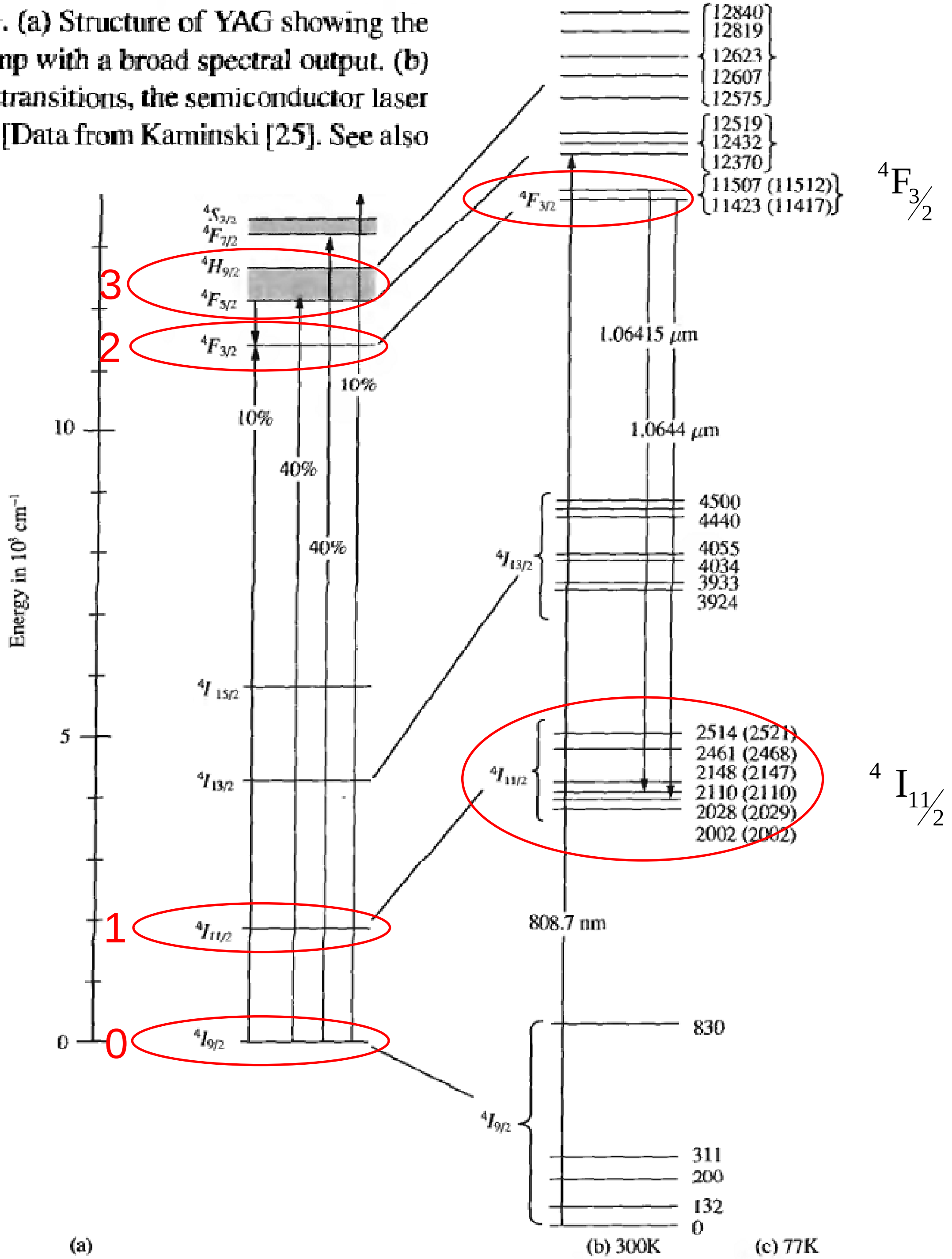


FIGURE 10.5. Energy level for neodymium in YAG. (a) Structure of YAG showing the pumping routes with the percentages referring to a pump with a broad spectral output. (b) Details of the manifold at 300 K showing the dominant transitions, the semiconductor laser pumping route is also shown. (c) Energy levels at 77 K. [Data from Kaminski [25]. See also Koechner [24].]



pumping to state (2):

1) flashlamp - 10% of the absorbed energy goes directly to ${}^4\mathrm{F}_{3/2}$

2) semiconductor laser $(\lambda = 808nm)$ - first to ${}^4\mathrm{F}_{5/2}$, ${}^4\mathrm{H}_{9/2}$ and then relaxes to ${}^4\mathrm{F}_{3/2}$

state (1): ${}^4\mathrm{I}_{11/2}$, $\tau_1 = 30ns$ decays to heat. YAG – high thermal conductivity

<u>operation:</u> CW, pulsed (mode locked or Q switched)

narrow line widths! => σ is large, but absorption lines are narrow.
(does not make good use of pumping – Xe or Kr lamps)

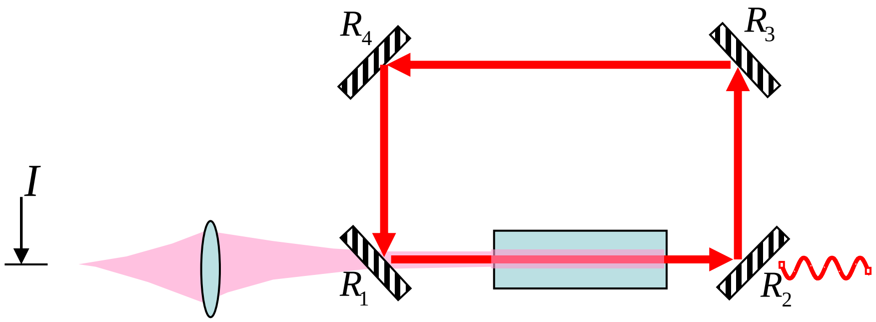
<u>Nd: YAG pumped by a semiconductor laser</u>

semiconductor lasers: (>40% conversion of electrical energy into radiation!
Power supply ~ flashlight batteries)

doubling techniques: $\dfrac{\lambda_0}{2} = \dfrac{1.064}{2} = 532nm$ (green)

allows “cigar box” size!

YAG ring pumped by a semiconductor laser



$T_1 \sim 1$ at λ_{pump}

$\lambda_{pump} = 808nm$

(into state 2) pumping to ${}^4\mathrm{F}_{5/2}$, or ${}^4\mathrm{H}_{9/2}$ then fast relaxation to ${}^4\mathrm{F}_{3/2}$

(out of state 1) ${}^4\mathrm{I}_{11/2}$ $\tau_1 = 30ns$ $N_1 \sim 0$

Calculations show (for details, see 10.4.3) that for:

pumping efficiency: $\eta_p = 90\%$

pump utilization efficiency: $\eta = 100\%$

saturation intensity at 1.064um: $I_s = \dfrac{h\nu}{\sigma_{eff}\tau_2} = 4.4 \frac{kW}{cm^2}$

survival factor: $S = 0.9$

threshold pump intensity:
$\Rightarrow I_{sp} = 676 \frac{W}{cm^2}$

For a mode size of $500\mu m$ diameter

pump power $\boxed{P = 1.33\ W}$ (reasonable with laser diodes)

Neodynium-Glass Lasers

amorphous glass
=> absorption bands are much broader than YAG
=> more efficient pump with flash lamp
=> but smaller σ for stimulated emission.

good for amplifiers because of large energy storage + wide bandwidth
=> amplification of very short pulses (~10ps)

low thermal conductivity
=> heat problem => low repetition rate

Erbium Doped Fiber Amplifiers (EDFA)

$\lambda = 1.55 \mu m$ - communication wavelength

Consider propagation from point A to B: $d_{AB} = 300 km$ $P_A = 10 mW$

(a) direct: total attenuation = $60 dB$

$\Rightarrow P_B = 10 nW$ (for 1ns pulse, ~ 78 photons)

=> repeater stations!

⇒ repeater stations (RS1, RS2, … ; spaced 100km) :

(b) Digital optical signal is detected, converted to high speed electronic logic, and the optical signal is regenerated. At RS1, signal down by 20dB and the current generated by a perfect detector: $P_{opt}/(h\nu/e) = 125\ \mu A$
To regenerate the signal and send it toward RS2 at the 10mW level, we must amplify the 125 μA back to the level required (10's of mA) and the digitally coded info re-established. The process is duplicated at RS2.

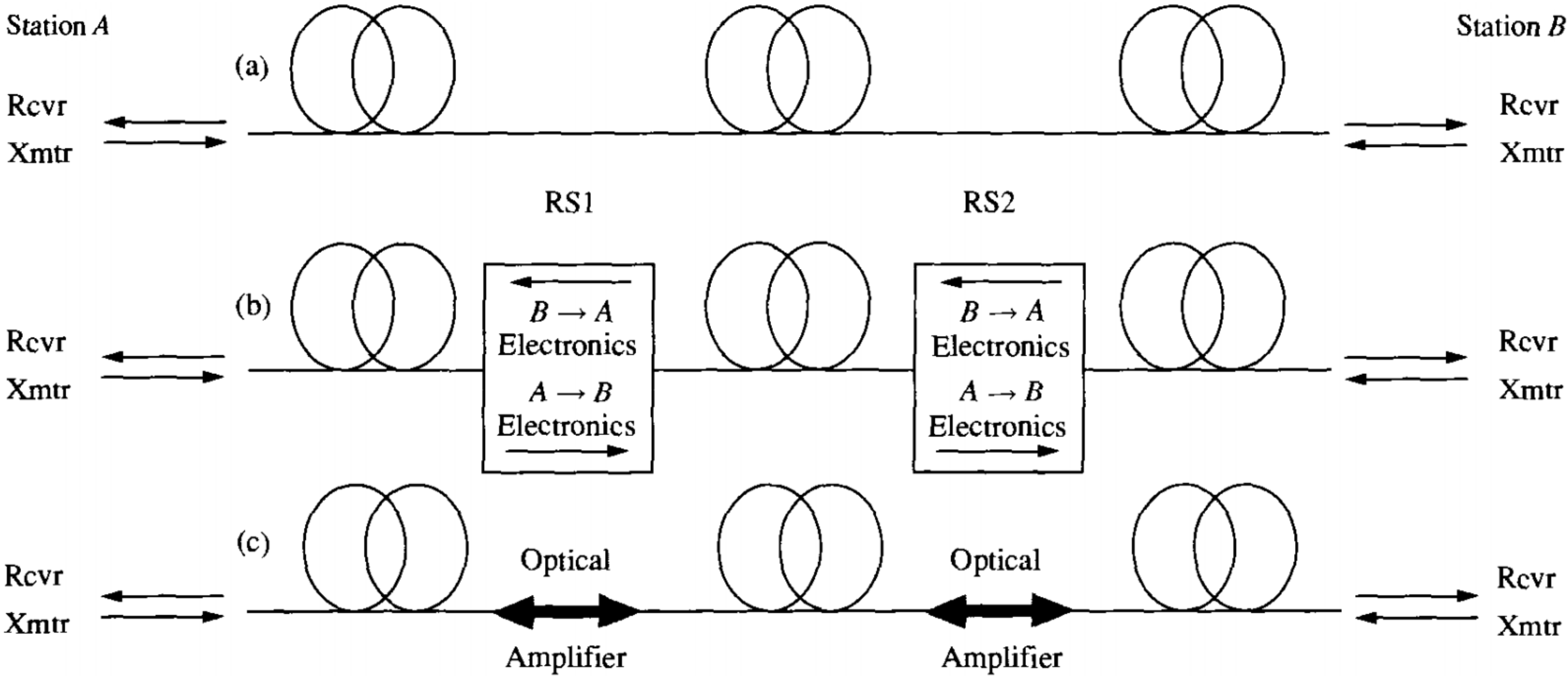
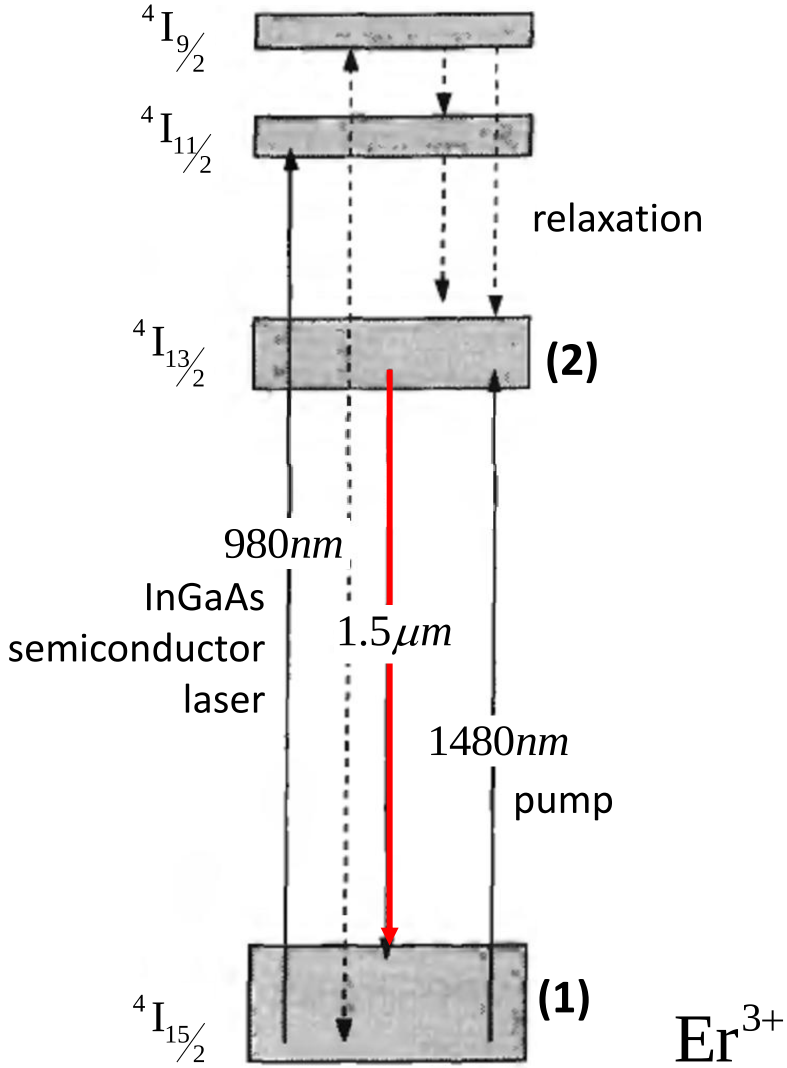


FIGURE 10.10. A long haul data link between stations A and B: (a) direct link; (b) detection and regeneration at the repeater stations; (c) optical amplifiers.

(c) The use of Optical Amplifiers at RS1 and RS2 greatly enhances and simplifies the performance.

- Optical Amplifiers are naturally bilateral: $\mathrm{B} \leftrightarrow \mathrm{A}$
- Only one pump, one power supply, and no fast regenerative electronics are needed.



~ 50 possible transistions between the $^4\mathrm{I}_{13/2}$ and $^4\mathrm{I}_{15/2}$ manifolds => wavelength division multiplexing (WDM) is possible.

$$\text{gain: } \gamma(v) = N_2\sigma_{em}(v) - N_1\sigma_{ab}(v)$$

$$(\sigma_{em} \neq \sigma_{ab} \quad \text{to be discussed later})$$

For pumping at ~1480nm, $N_1 + N_2 = N$ (Er density)

For optical transparency at v_1

$$\gamma(v) = 0 = N_2\sigma_{em}(v) - N_1\sigma_{ab}(v)$$

$$\Rightarrow \frac{N_2}{N_1} = \frac{\sigma_{ab}(v)}{\sigma_{em}(v)} \qquad N_1 + N_2 = N \Rightarrow N_1 = N - N_2$$

$$\Rightarrow N_2 = N\frac{\sigma_{ab}(v)}{\sigma_{em}(v) + \sigma_{ab}(v)}$$

Manifold (2) $^4\mathrm{I}_{13/2}$ decays by radiation back to the ground state (1) $^4\mathrm{I}_{15/2}$ at rate $\frac{1}{\tau_2}$ => the pump must supply this fluorescence power:

$$\frac{P}{vol.}(\text{opt.transp.}) = h\nu \frac{N}{\tau_2} \frac{\sigma_{ab}(\nu)}{\sigma_{em}(\nu) + \sigma_{ab}(\nu)} \qquad \tau_2 \simeq 10 \text{ ms}$$

The stimulated emission σ is small, as is the doping density, => tens of meters of doped fibers are needed to establish the 30 to 40 dB gain required to compensate for the fiber loss. Such amplifiers are pumped from one end, and thus the 980nm (or 1480nm) must be injected into the fiber through a coupler.