Optical and Photonic Glasses

Lecture 36:

Fiber Lasers and Amplifiers

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For New Functionality in Glass

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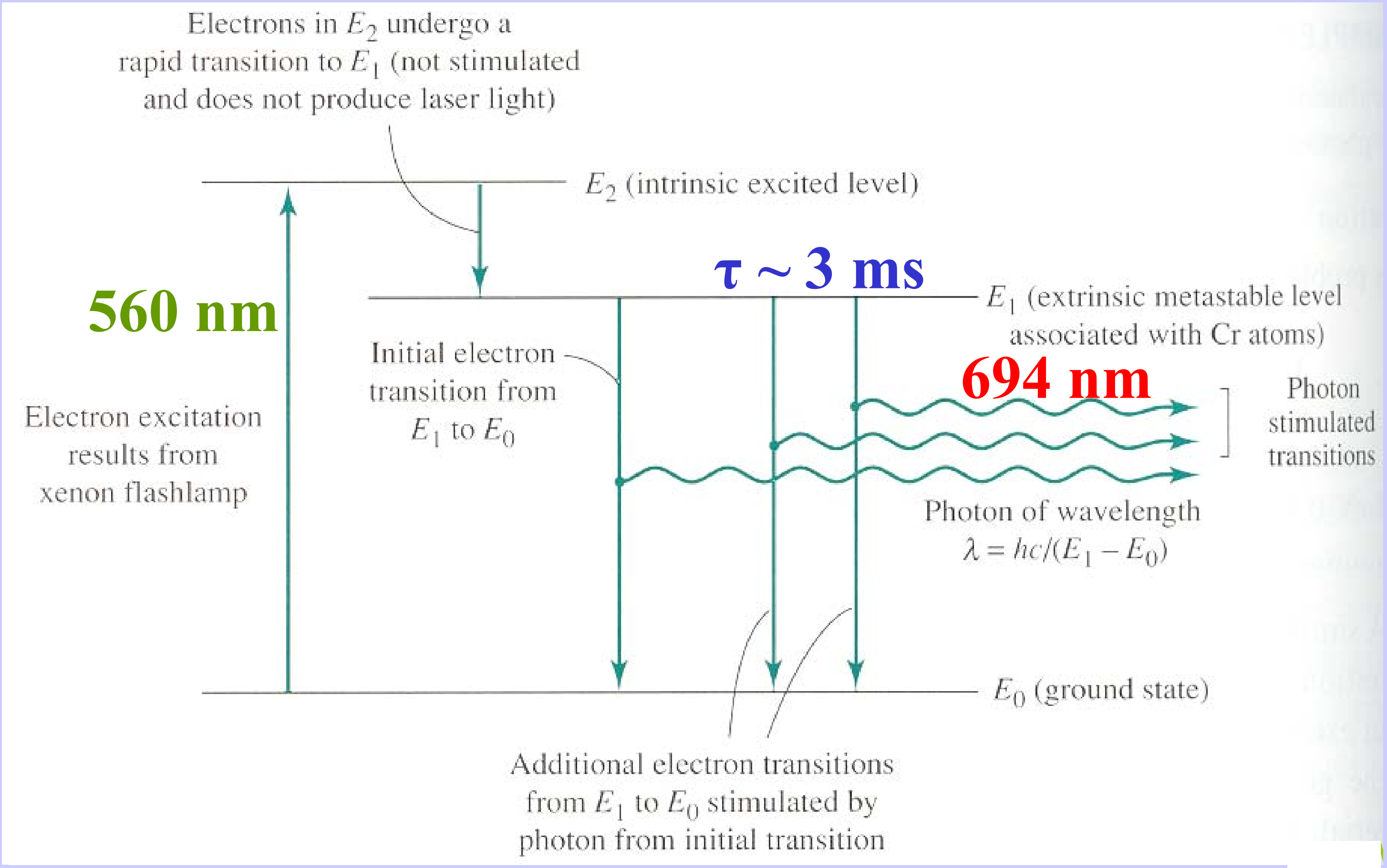
At least 3 energy levels are needed to achieve population inversion in a laser.

Example of the ruby laser

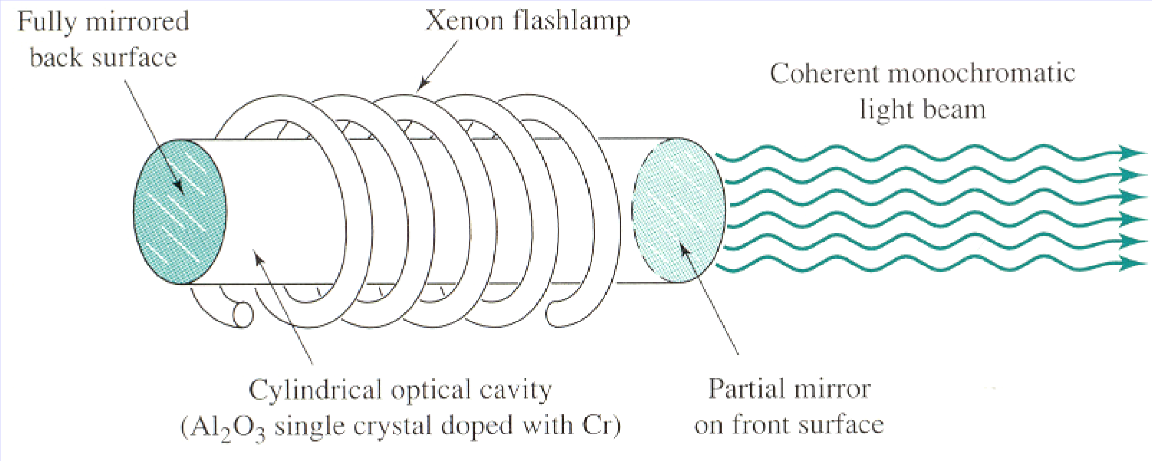


(Adapted from: *The science and design of engineering materials*, J.P. Schaffer, McGraw-Hill, 1999)

Example: the **ruby laser**

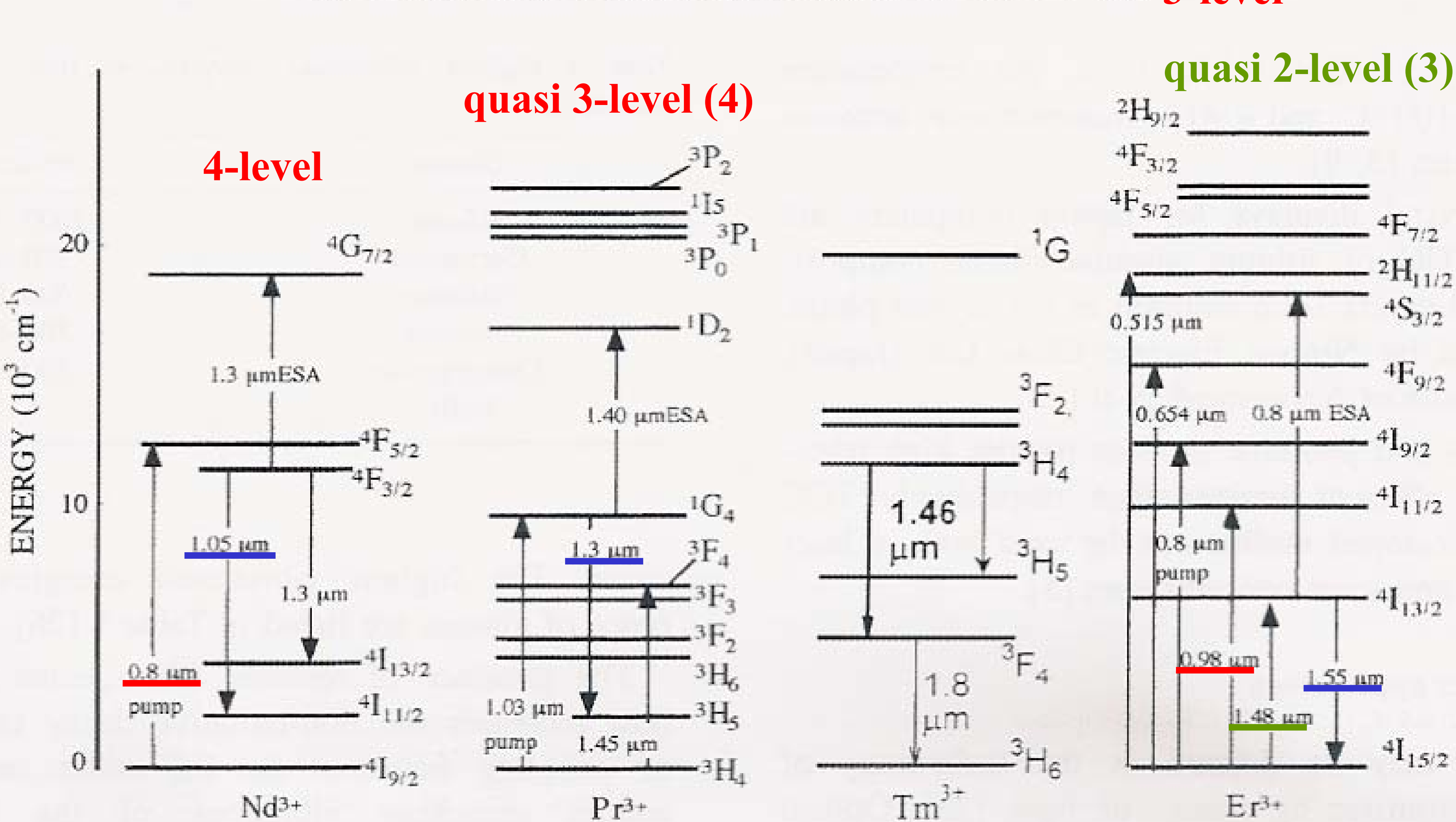
The ruby is a corundum (Al_2O_3) crystal doped with ~ 0.05% Cr^{3+} (a substitutional transitional metal ion impurity which gives it its characteristic red color), corresponding to a 3-level laser system which can be pumped @ 560 nm (by a Xe flash lamp) to an excited level, from which it decays non-radiatively to a metastable level ($\tau \sim 3$ ms), followed by fluorescent emission @ 694.3 nm to the ground state.

The crystal is polished with two highly parallel faces, one of them being 100% mirrored, whereas the other is only partly (~ 50%) mirrored. After pumping, only those 694.3 nm *stimulating* photons (spontaneously emitted) and the *stimulated* photons (of the same energy, phase and polarization as the former) which travel perpendicularly (in a highly collimated fashion) to the crystal faces will participate in the *cascade* process. This will end in a final light pulse (with a 0.6 ms duration) which leaves the partially mirrored face of the crystal.



(Adapted from: SSASW)

M. Clara Gonçalves et al. / C. R. Chimie 5 (2002) 845–854

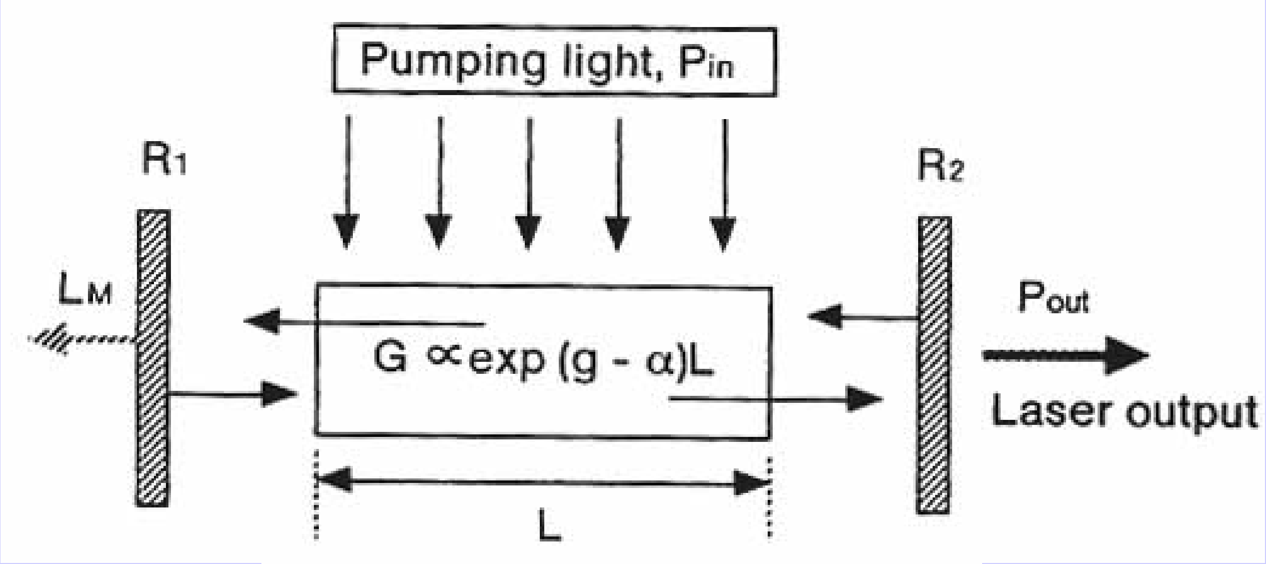


Simplified electronic energy level diagrams of three different RE ions and relevant transitions for pumping and emission.

Assuming a gain per unit length of g in a glass laser of length L and having mirrors with reflectivities R_1 (100%) and R_2 (~ 50%), the light intensity is amplified by a factor of exp(gL) in each passage through the material. However, there will be reflection, scattering and absorption losses in the elements of the laser cavity, which can be grouped into a single loss coefficient per unit length, α. Thus, the loop gain on every complete two-way passage of the light through the laser cavity is:

$$G = R_1 R_2 \exp[2(g-\alpha)L]$$

The condition for continuing oscillation is thus G = 1.



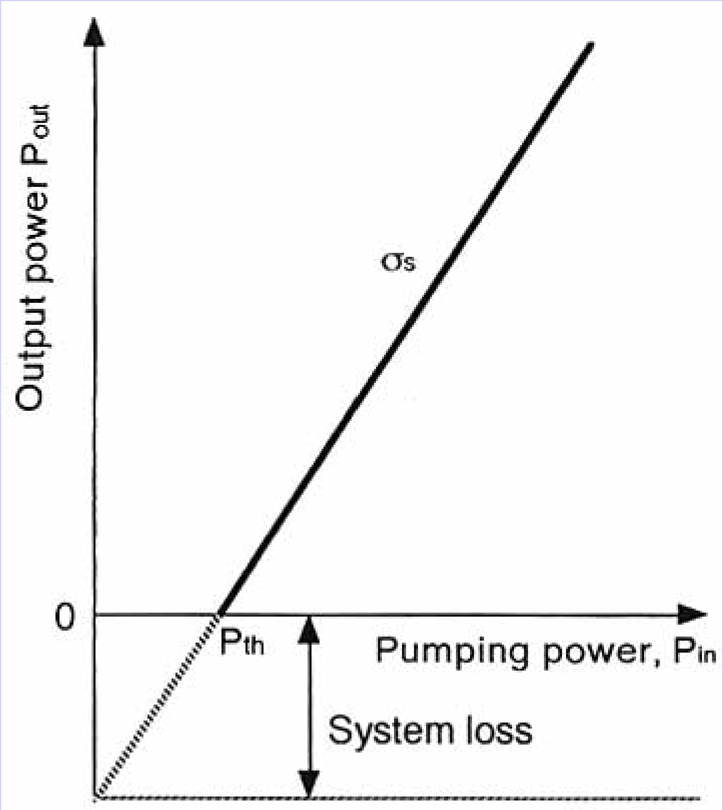
Typical laser oscillator configuration.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Assuming that the pump rate is a linear function of the input pump power, P_{in}, the population inversion is a function of the pump intensity and the output power, P_{out} is a function of P_{in}:

$$P_{out} = \sigma_s (P_{in} - P_{th})$$

where P_{th} is the minimum required, or *threshold*, input power and σ_s is the *slope efficiency* of the laser curve. P_{th} is higher for a 3-level laser than for a 4-level one (as shown below).



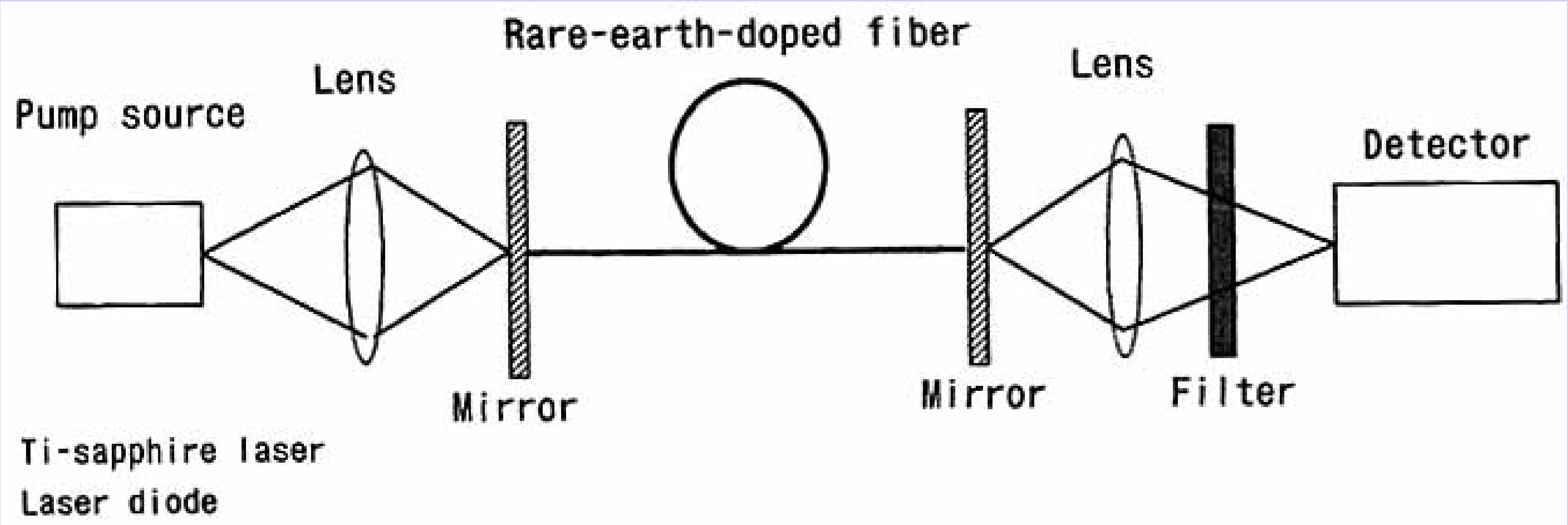
Output power versus pump input for a four-level system.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

RE-doped **fiber lasers** can be used in both long-haul (1.5 μm) and local area network (1.3 μm) communications, as optical amplifiers. Such systems typically use *single mode* fibers, for which the V-number ($V = \pi\, d\, NA / \lambda$) must be < 2.405.

The tight confinement of light in a fiber helps the achievement of a large population inversion density and glass fiber lasers readily operate in CW mode, at room temperature, without the need for cooling.

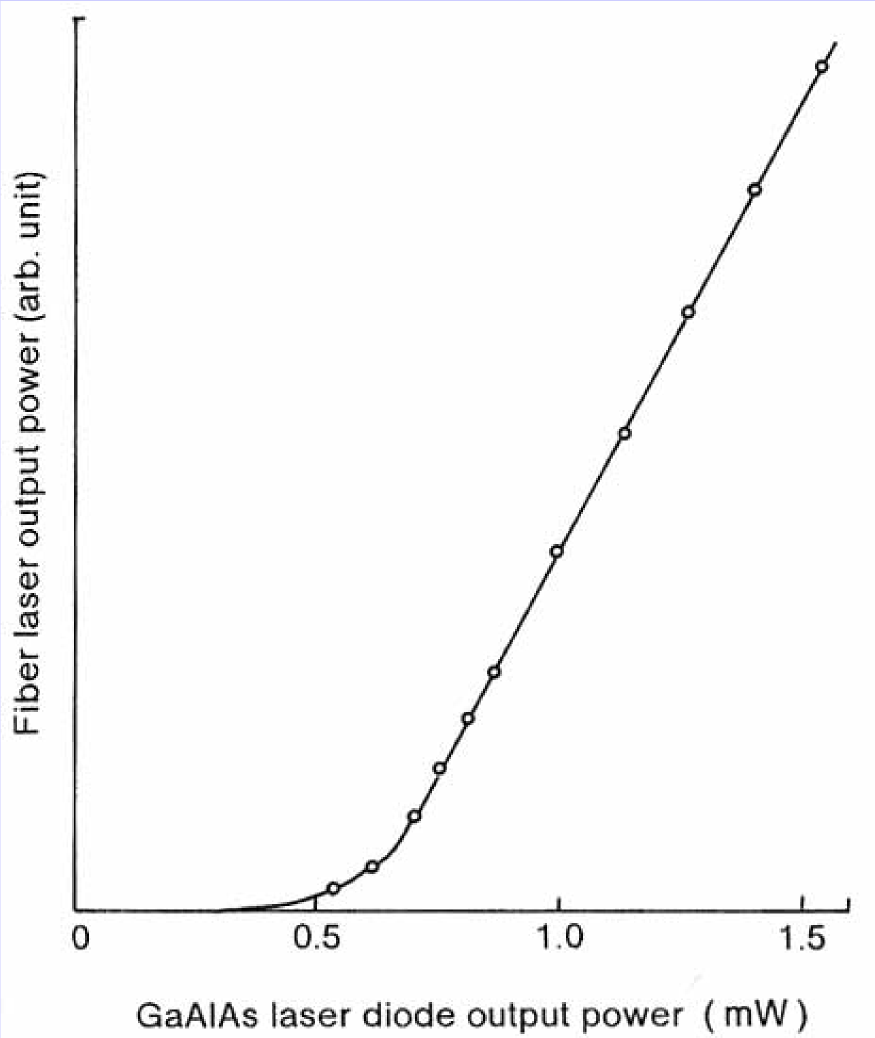
A RE-doped silica fiber preform is usually made by the CVD technique, using small quantities of $NdCl_3$, e.g., during the core deposition, or by soaking a porous preform in a solution of $NdCl_3$, before dehydrating, sintering and collapsing the preform.



Typical configuration of fiber laser oscillator.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Typical output power vs. pump power curve for a fiber laser oscillator

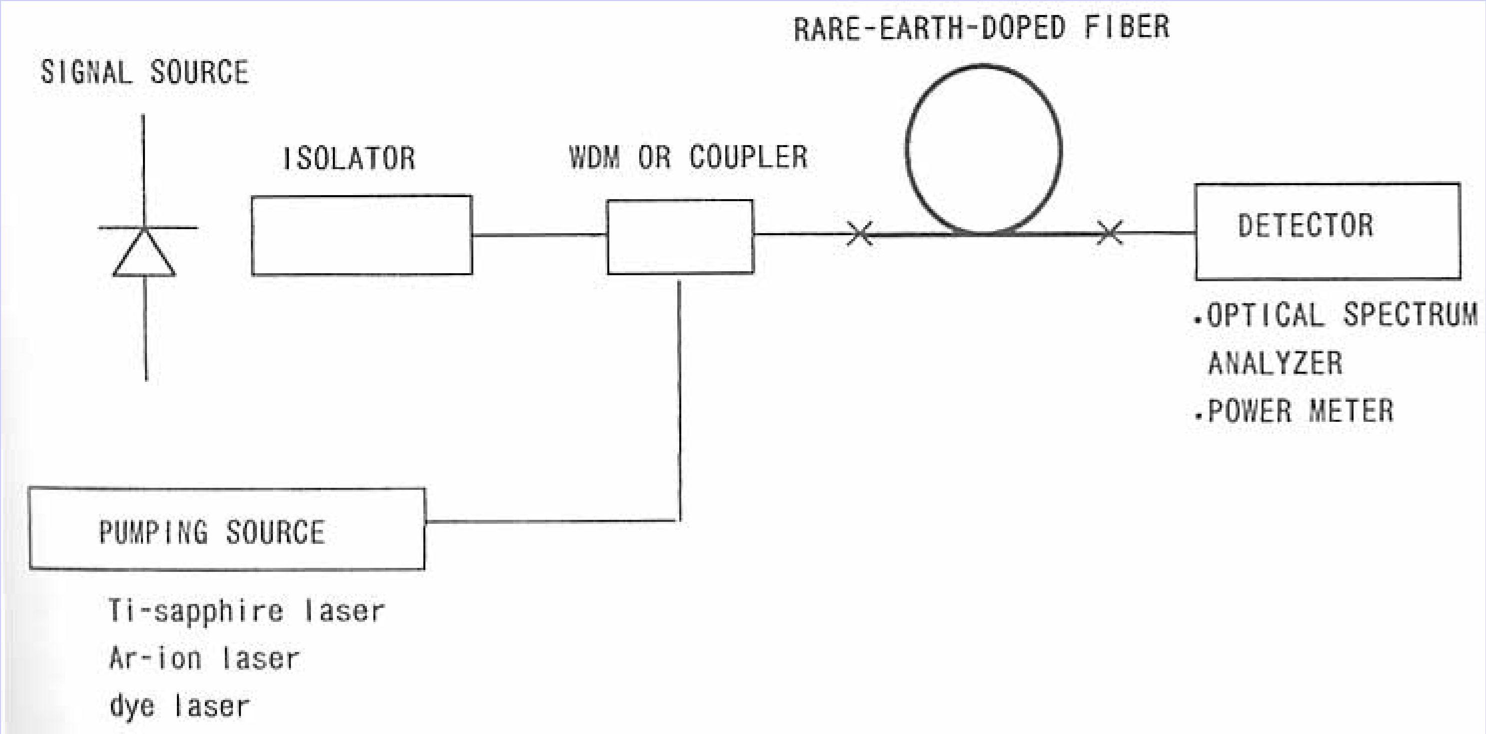


Typical example of the output power as a function of pump power. [Reprinted from R. J. Mears, L. Reekie, S. B. Poole and D. N. Payne, *Electron. Lett.* **21** (1985) 738, copyright (1985) with permission from the Institute of Electrical Engineers.]

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Fiber amplifiers

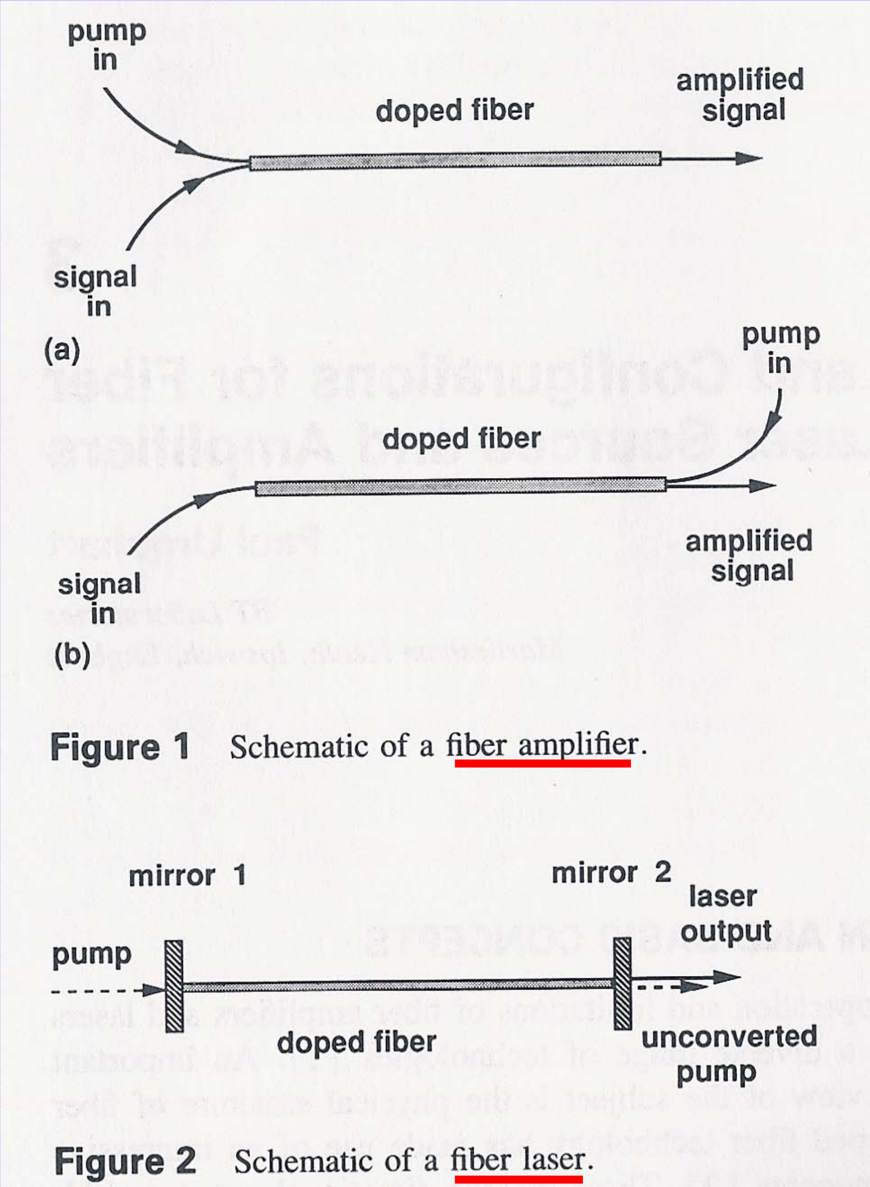
The driving force for the development of RE-doped fiber amplifiers was their application in fiberoptics operating at 1.5 μm, or the installed systems at 1.3 μm. It suffices to splice a section of RE-doped fiber into the transmission fiber and injecting into it pump light through a fiber coupler, as shown below. The signal will stimulate emission of the excited RE ions, thus amplifying that same signal.



Typical experimental configuration of fiber optical amplifier.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Schematic comparison between fiber laser resonators and fiber amplifiers

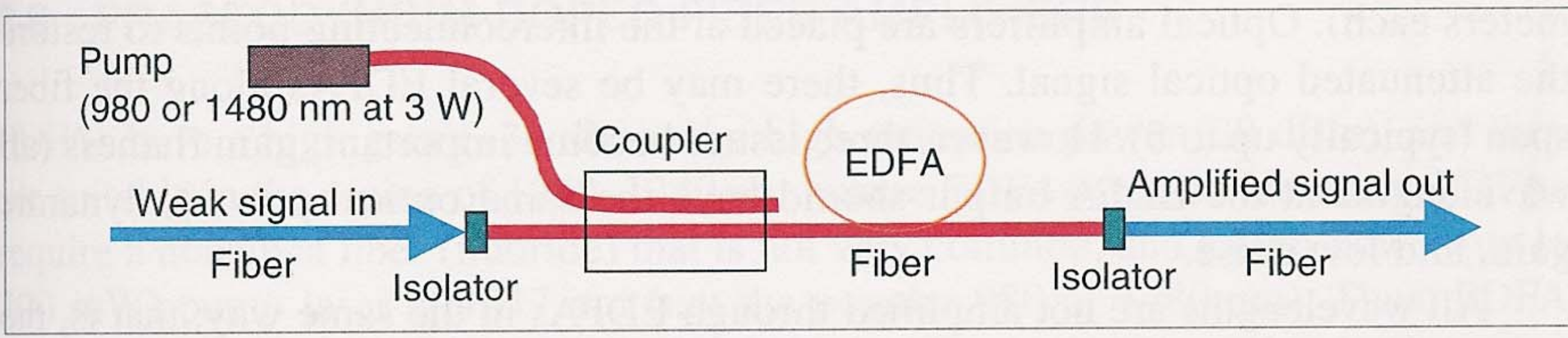


(Adapted from: *Rare earth doped fiber lasers and amplifiers*, M.J.F. Digonnet, Marcel Dekker, 1993)

A fiber laser differs from a fiber amplifier in that : (1) each fiber laser end must be coupled to a mirror which provides reflection at the signal wavelength; (2) no signal is injected into the laser cavity. The laser signal grows from ASE and the laser output power is directly proportional to the excess pump power above P_{th}.

A fiber amplifier is a section of doped fiber; pump and signal waves are launched into this fiber at either the same end, or at opposite ends and the amplified signal emerges at the opposite end from which the signal was launched.

Erbium Doped Fiber Amplifier



An EDFA amplifier consists of an erbium-doped silica fiber, an optical pump, a coupler, and isolators at both ends.

(Adapted from: *Introduction to DWDM technology*, S.V. Kartalopoulos, IEEE Press, 2000)

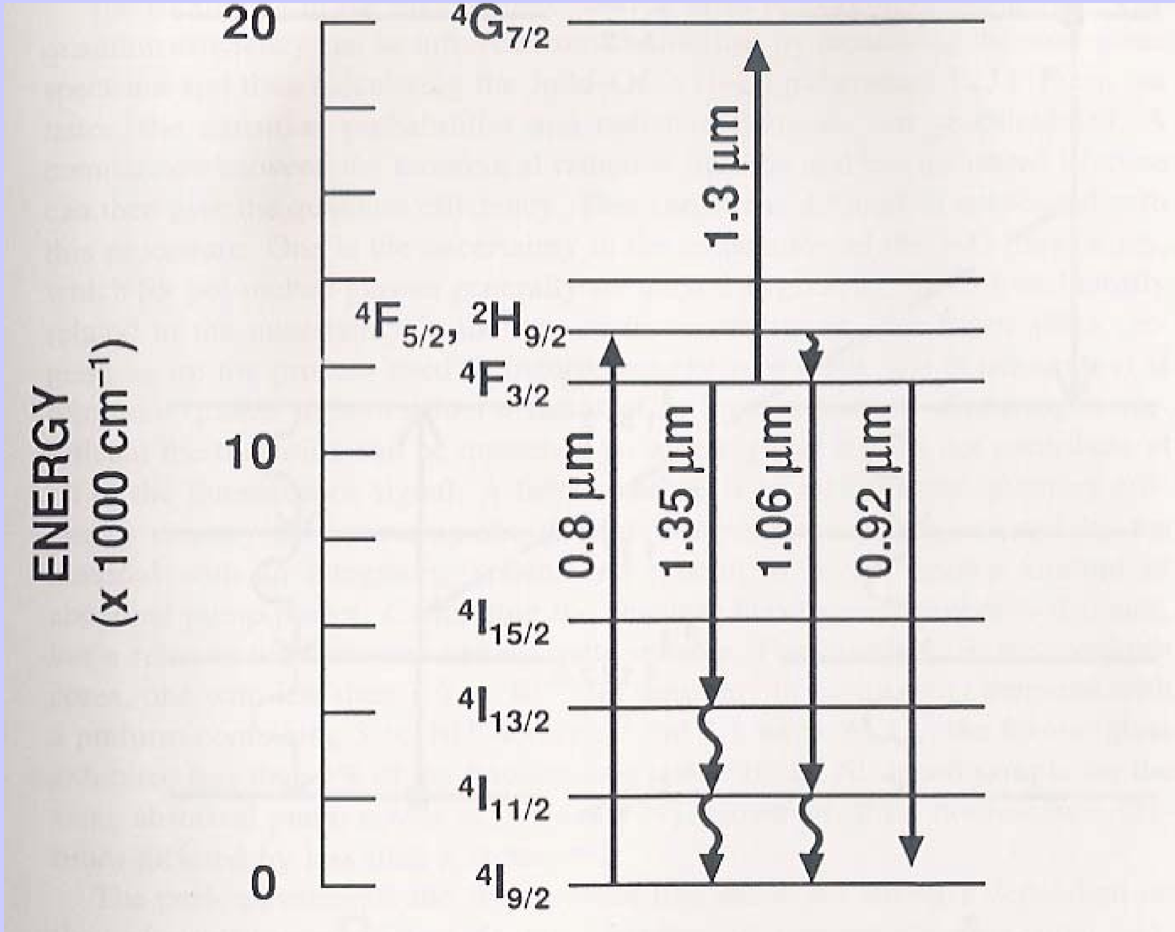
Among the dissipative processes which remove excited RE ions from the initial (metastable) lasing level and which therefore control the efficiency of an amplifier, are: (1) MP relaxation directly to the next lower energy level (via glass matrix or impurity vibrations); (2) up-conversion, either via ESA, or by the co-operative mechanism; (3) cross-relaxation; and (4) the Amplified Spontaneous Emission (ASE) process.

ASE is the efficient amplification of spontaneous emission from the metastable level, via another transition starting in the same upper lasing level and having a high branching ratio (β), which causes *gain saturation* at the wavelength of interest.

A typical example is Nd^{3+}, where the stimulated emission cross section and β for the 1.35 μm transition are ~ four times smaller than for the 1.06 μm transition. Thus the spontaneous emission at 1.06 μm will be amplified more efficiently and saturates the available gain at 1.35 μm. Some improvement may be achieved by filtering out the 1.06 μm ASE.

The **figure of merit** of an **amplifier** is proportional to the product, $\boldsymbol{\sigma \tau}$, of the stimulated emission cross section and the metastable level lifetime.

ASE in Nd^{3+}-based amplifiers



Energy level diagram of Nd^{3+}-doped silica showing the pump band at 0.8 µm and the fluorescence transitions near 0.92, 1.06, and 1.35 µm. Nonradiative transitions are indicated by wavy arrows.

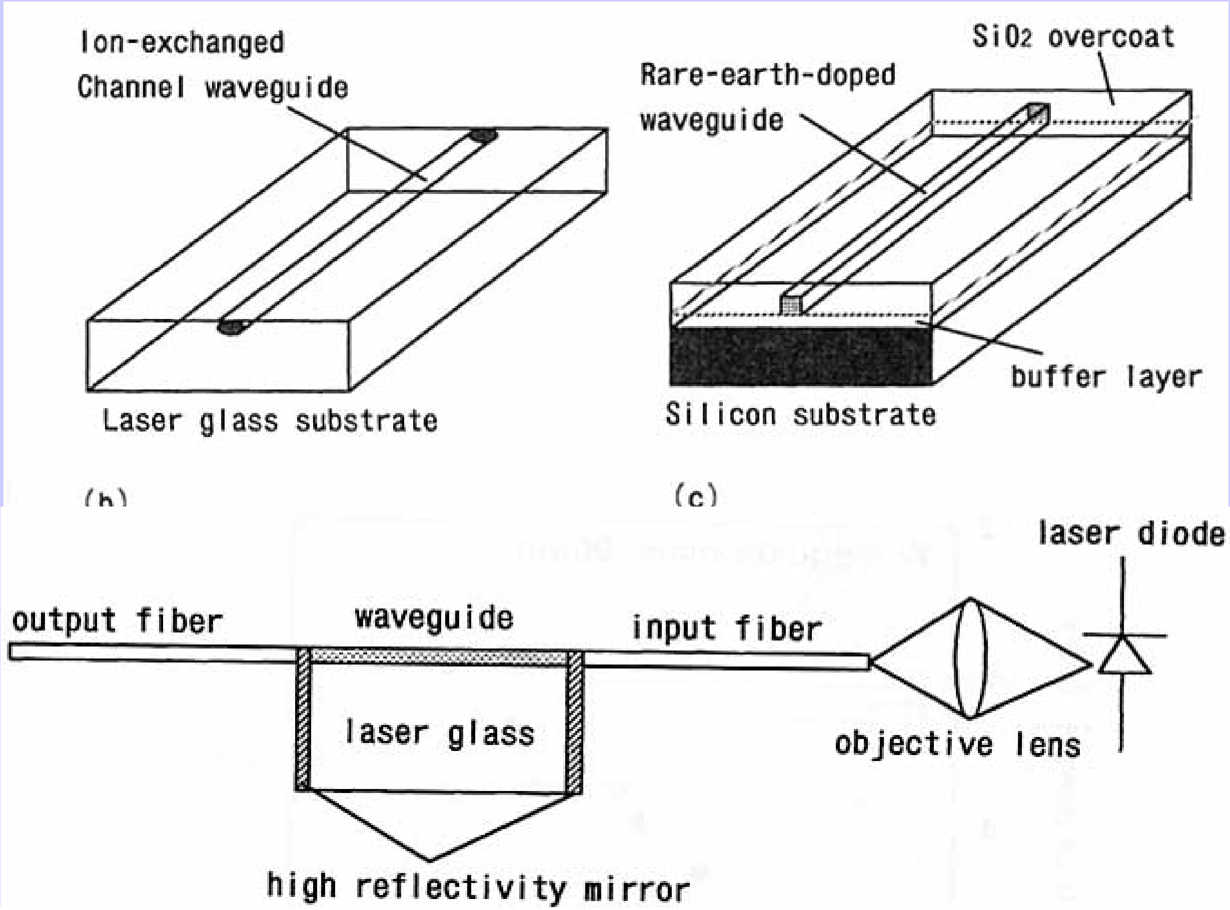
(Adapted from: *Rare earth doped fiber lasers and amplifiers*, ed. M.J.F. Digonnet, Marcel-Dekker, 1993)

Waveguide lasers and amplifiers

Glass in thin film form is the basis of integrated optical components, both passive and active (e.g. RE-doped). RE-doped glass planar (or channel) waveguides allow the fabrication of more compact and efficient laser and amplifier devices. In particular, Nd and Er-doped waveguide lasers and amplifiers, fabricated by a variety of methods, have received increasing attention for optical amplification @ 1.3 μm and 1.5 μm, but also as potential high power laser sources.

Waveguides can be fabricated by ion-exchange, ion implantation, flame hydrolysis, CVD, sputtering or electron beam and sol-gel deposition techniques.

The next figure shows a *channel waveguide* structure (b) fabricated by ion-exchange and a ridge waveguide structure (c) fabricated by FHD and RIE. A laser cavity (a) is formed by two mirrors coated on the cleaved ends of the waveguide, or by dielectric mirrors butted on the same ends.



(a) Typical configuration of waveguide laser oscillator and structure of waveguide laser fabricated by (b) ion exchange technique and (c) flame hydrolysis deposition and reaction ion etching technique. [(a) reprinted from H. Aoki, O. Maruyama and Y. Asahara, *IEEE Photonics Technol. Lett.* **2** (1990) 459, copyright (1990) with permission from the Institute of Electrical and Electronics Engineers, Inc. (c) reprinted from T. Kitagawa, K. Hattori, M. Shimizu, Y. Ohmori and M. Kobayashi, *Electron. Lett.* **27** (1991) 334, copyright (1991) with permission from the Institute of Electrical Engineers.]

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)