II Spectroscopy of rare-earth ions: Light-matter interactions

Consider an ensemble of N atoms forming a lasing medium. Each atom exhibits two energy levels such that the energy difference is $\Delta E = h\nu_{12} = hc/\lambda_{12}$. The concentration (in ions/m^3) of the upper level is N_2, while that of the lower level is N_1. At all times, $N = N_1 + N_2$.

We now consider photons travelling through this medium. There are three types of light-matter interaction: absorption, spontaneous emission and stimulated emission.

II.1 Absorption

If photons of frequency ν_{12} pass through the medium, there is a possibility of the light being absorbed by electrons in the ground state (1). Electrons are excited in the upper state (2). N_1 decreases. N_2 increases. This corresponds to a net loss in terms of photons.

In usual (undoped) silica fibers operated at near-infrared frequencies, absorption is very low, on the order of 0.2 dB.km^{-1} at 1550 nm, because (a) SiO_2 glass does not present absorption transitions at these frequencies and (b) no unwanted impurities, that could present absorption transitions at these frequencies, are introduced in the fiber preform during the MCVD process. After 15 (resp. 100) km of propagation, the input power P_{in} has been reduced by a factor of 2 (resp. 100). This very low attenuation level explains why the modern telecommunication systems are operated at 1550 nm.

In RE-doped fibers, however, the absorption is usually very high at specific wavelengths. As shown in Fig. 3a , the attenuation level of an Er^{3+}-doped fiber was measured to 70 dB/km at 650 nm, 80 dB/km at 980 nm, and 110 dB/km at 1530 nm for a low concentration of only 2 parts of Er^{3+} in 10^6.

As shown in the energy level diagram of Er-doped glass (Fig. 3b), the three absorption peaks can be attributed to three absorption transitions from the ground state. The 160 dB.km^{-1} peak at 1390 nm, however, does not correspond to any absorption transition in Er^{3+}. It is attributed to unwanted chemicals (hydroxyl group OH^-) resulting from presence of water in the fiber preform.

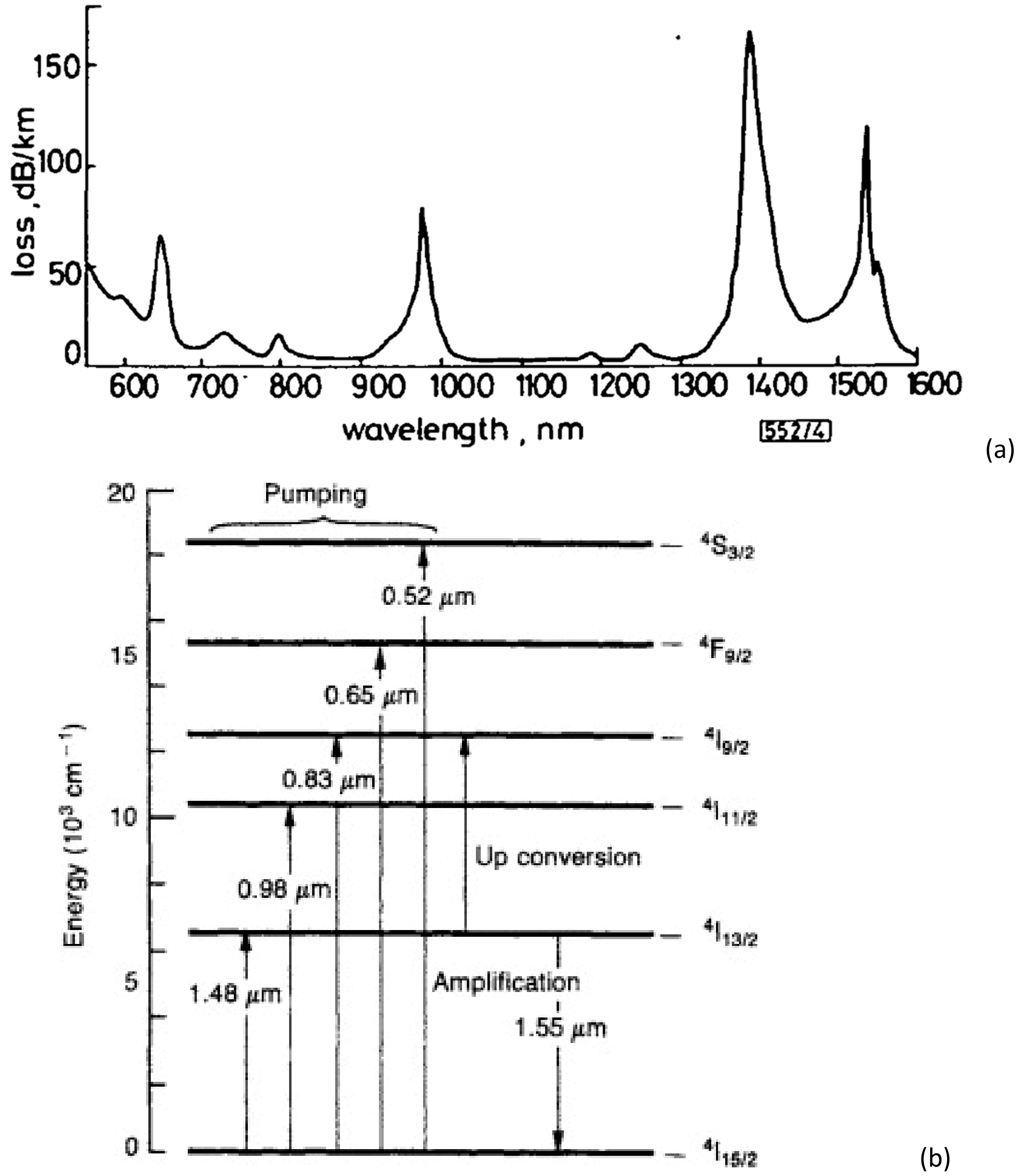
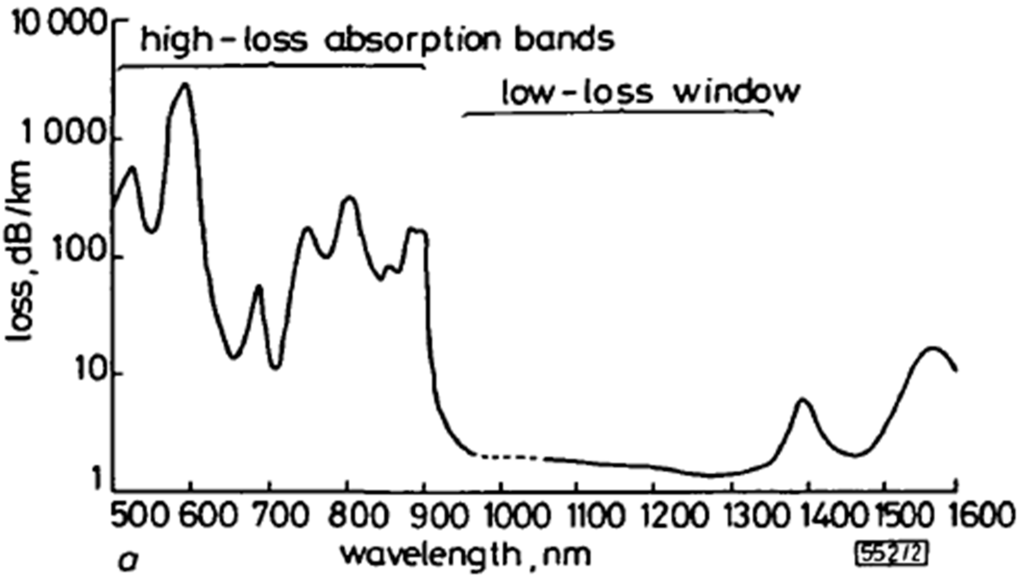


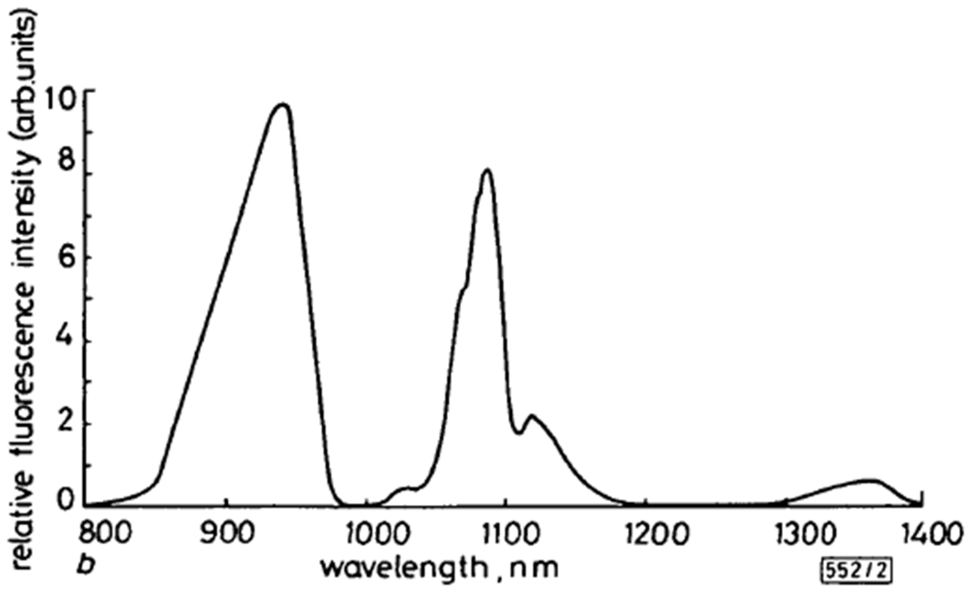
Fig.3 (a) Absorption spectrum of fiber containing 2 parts in 10^6 of Er^{3+} (from S. B. Poole and D. N. Payne, and M. E. Fermann "Fabrication of low-loss optical fibres containing rare-earth ions," in *Electronics Letters*, vol. 21, no. 17, pp. 737-738, 15 August 1985). **(b) Energy level diagram for Er^{3+}.**

II.2 Spontaneous emission

Now, suppose atoms are initially in state (2) because of photons' absorption for example. Spontaneous decay events to the lower state (1) may occur. The system releases energy in the form of a photon of frequency ν_{12}, which increases the population N_1 of the lower state. Note that the photons are emitted stochastically: there is no phase relationship between photons emitted from a group of atoms in the upper level. Spontaneous emission is said to be incoherent. The fluorescence spectrum originates from spontaneous emission. As an example, Fig. 4 shows the absorption (a) and emission (b) spectra of Nd^{3+}. Of course, the fluorescence spectrum can be correlated to the laser transitions in the energy level diagram. Fig. 5 shows the laser transitions for trivalent RE in glass hosts and corresponding energy levels.



(a)



(b)

Fig. 4 (a) Absorption spectrum of fiber containing 30 parts of Nd^{3+} in 10^6 parts. (b) Fluorescence spectrum of fiber containing 300 parts of Nd^{3+} in 10^6 parts.

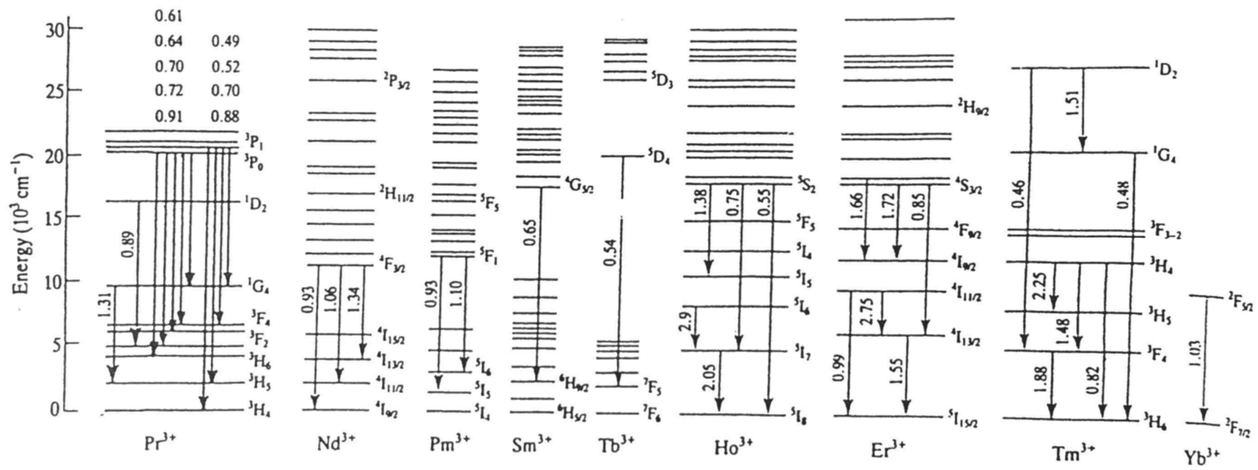


Fig. 5 The laser transitions for trivalent RE in glass hosts and corresponding energy levels.

It is clear from Fig. 4b and Fig. 5 that the emission peaks obtained at 930 nm and 1060 nm when Nd^{3+} is pumped at 808 nm can be attributed to the laser transitions $^4F_{3/2} \rightarrow {}^4I_{9/2}$ and $^4F_{3/2} \rightarrow {}^4I_{11/2}$, respectively.

II.3 Stimulated emission

Stimulated emission occurs when an atom in the upper level is de-excited by a nearby photon that has the correct frequency ν_{12}, matching the energy gap. In this case the relaxation to the lower state is accompanied with the emission of a photon with frequency ν_{12}, as well. Since the original photon is not absorbed (the energy level is already occupied), this interaction results in the production of a twin photon. The process of stimulated emission is coherent and is at the core of any laser. **<u>LASER means light amplification by stimulated emission of radiation.</u>**