**Radiation-balanced (athermal) laser**

Traditional solid-state amplifiers or lasers are exothermic. Heat generated inside the amplifier or laser medium, which is caused by the quantum defect, is a source of increased temperature and stress. It causes poor beam quality and limits the average output power. In 1999, Bowman proposed a radiation-balanced (athermal) laser, in which lasing is accomplished by offsetting the heat generated from stimulated emission by the anti-Stokes cooling effect (Bowman 1999). Let us consider the basic concepts of a radiation balanced (athermal) laser, in which lasing and anti-Stokes cooling occur in the same system of ions doped in the crystal or glass host. Figure 1 illustrates the energy-level diagram of a laser system, where the quantum energy defect is only of the order of $k_B T$. A solid-state laser of this type can be often referred to as a quasi-three-level laser. The upper and lower electronic levels (manifolds) are split into many closely spaced sublevels. The population of each sublevel within a manifold is described by Boltzmann occupation factors. We assume that transitions between these sublevels are purely nonradiative transitions, provided by phonon absorption and emission. The energy gap between sublevels is much less that $k_B T$ thus intra-band thermalization occurs on a picosecond time scale. Assume that radiative lifetime of the upper manifold is on the order of milliseconds and the transitions between the upper and lower manifolds (inter-band relaxation) are purely radiative, since a bandgap between the upper and lower manifolds is large compared to the energies of the phonons. We also assume the absence of excited-state absorption, energy transfer, and absorption by nonradiative background transitions. The laser is pumped at a frequency $\nu_p$. $\nu_l$ is the frequency of the laser field, and $\nu_f$ is the mean fluorescence frequency. The total density of the ions in the host, $N_T$, is equal to the sum of the densities of ions in the first (ground), $N_1$, and second (excited), $N_2$, manifolds:

$$N_T = N_1 + N_2.$$  \hspace{1cm} (1)

The rate equation of the upper level follows as
\[
\frac{dN_2}{dt} = W_p - W_l - \frac{N_2}{\tau},
\]

where \( \tau \) is the fluorescence lifetime, \( W_p \) is a pump rate, and \( W_l \) is a stimulated emission rate described by the equations:

\[
W_p = \frac{I_p}{h\nu_p} \left[ N_2 \sigma_p^a - N_2 \left( \sigma_p^a + \sigma_p^{se} \right) \right],
\]
\[
W_l = \frac{I_l}{h\nu_l} \left[ N_2 \sigma_l^a + \sigma_l^{se} - N_2 \sigma_l^a \right]
\]

where \( I_{p,l} \) are intensities of the pump (\( p \)) and the laser (\( l \)) beams. \( \sigma_{p,l}^{a,se} \) are the cross sections of the absorption (\( a \)) and stimulated emission (\( se \)) at the pump (\( p \)) and the laser (\( l \)) wavelengths. In the steady state, \( dN_2/dt = 0 \) and Eq. (1) can be written as

\[
W_p = W_l + \frac{N_2}{\tau}.
\]

Note that for radiation-balanced amplification, the absorbed power density has to be equal to the radiated power density at any point in the laser medium (Bowman 1999):

\[
h\nu_p W_p = h\nu_l W_l + h\nu_f \frac{N_2}{\tau}.
\]

Eq. (5) valid only for the athermal laser, is not applicable to a traditional exothermic laser in which the Stokes energy shift between the pump photons (\( h\nu_p \)) and the laser photons (\( h\nu_l \)) appears as heat in the amplifier medium. The relation for laser gain can be described by the well-known equation

\[
\frac{dP_l}{dz} = \left[ (\sigma_l^a + \sigma_l^{se})N_2 - \sigma_l^a N_T \right] P_l.
\]

Substituting Eqs. (3), (4), and (5) into Eq. (6) one can obtain the equation, which describes the laser signal at any point, \( z \), along the length of the laser medium.

\[
\frac{P_l(0)}{P_l(z)} \exp \left( \frac{P_l(z) - P_l(0)}{P_{sat}} \right) = \exp \left( \sigma_l^a N_T z \right),
\]

where
\[ P_{l}^{\text{Sat}} = A_{\text{eff}} \frac{h v_{l}}{\tau (\sigma_{l}^{a} + \sigma_{l}^{te})} \left( \frac{v_{f} - v_{p}}{v_{p} - v_{l}} \right) \]  

(8)

is the saturation power of the laser signal and \( A_{\text{eff}} \) is the effective area of the mode, which supports the laser signal. To support growth of the laser signal for one-way propagation described by Eq. (7) and to keep the radiation balance at each point in the laser medium, the pump power has to be \textit{distributed properly} along the length of the laser medium. This distribution can be obtained with the help of Eqs. (3) - (5):

\[ P_{p}(z) = \frac{\sigma_{l}^{a} (\sigma_{l}^{a} + \sigma_{l}^{te}) P_{l}(z) P_{l}^{\text{Sat}}}{(\sigma_{p}^{a} \sigma_{l}^{te} - \sigma_{l}^{a} \sigma_{p}^{te}) P_{l}(z) - \sigma_{p}^{a} (\sigma_{l}^{a} + \sigma_{l}^{te}) P_{l}^{\text{Sat}}}, \]  

(9)

where

\[ P_{l}^{\text{Sat}} = A_{\text{eff}} \frac{h v_{p}}{\tau (\sigma_{p}^{a} + \sigma_{p}^{te})} \left( \frac{v_{f} - v_{l}}{v_{p} - v_{l}} \right). \]  

(10)

is the saturation power of the pump signal. It is easily seen from Eq. (9) that radiation-balanced amplification requires careful control of the pump power distribution along the laser medium. Since the value of the pump power has to be \( P_{p} > 0 \), in the case of the athermal laser for each combination of the host material, ions, pump and signal wavelengths, there is a minimum value of laser power inside the laser cavity as can be seen from Eq. (9), and is:

\[ P_{l}^{\text{min}} = A_{\text{eff}} \frac{h v_{p} \sigma_{p}^{a}}{\tau (\sigma_{p}^{a} \sigma_{l}^{te} - \sigma_{l}^{a} \sigma_{p}^{te})} \left( \frac{v_{f} - v_{p}}{v_{p} - v_{l}} \right), \]  

(11)

which can be amplified athermally. This minimum intensity can serve as a figure of merit in the selection of material and operating frequency for a radiation-balanced laser. As one can see from Eqs. (4) and (5) for radiation-balanced operation of a laser the mean fluorescence frequency, the pump and laser frequencies have to satisfy to the relation: \( v_{f} > v_{p} > v_{l} \). A comprehensive theory of the radiation-balanced bulk solids-state laser has been presented in the work of Bowman (Bowman 1999) and enhanced for the case of the thermal fiber amplifier in the paper (Nemova & Kashyap 2009a). Figure 2 illustrates the evolution of the athermally amplified signal and pump power, which provides this athermal amplification, with the length of the fiber amplifier for three different input signal powers. This Yb\(^{3+}\)-doped amplifier based on ZBLAN fiber with a radius of the
core \( r_{co} = 70 \mu m \). Yb\(^{3+}\) ion concentration \( \rho \approx 2.42 \times 10^8 \) ions/\( \mu m^3 \) permits it to be free from any co-operative interactions. As one can see in Fig.2 the power of the amplified signal changes *almost linearly* with the length of the amplifier for radiation-balanced amplification. The *linear* growth of the power of the amplified signal requires an enormous increase in the length of the fiber for very high output power. The precise control of the pump power and almost linear growth of the amplified signal are two serious obstacles in the practical development of radiation-balanced amplifiers and lasers. Analysis of the sensitivity and stability of a radiation-balanced laser to perturbations in the field parameters and temperature has been made (Bowman *et al.* 2002a). It was shown that fluctuations in the gain set limits on the variability of the pump wavelength. A pump stability of \( \pm 1 \) nm is suggested for a Yb:KGW laser. An active wavelength stabilization scheme is proposed to minimize the sensitivity of the athermal laser to ambient temperature fluctuations. Thermodynamics of the radiation-balanced laser has been comprehensively analysed by Mungan (Mungan 2003). The Carnot efficiency has been derived for all-optical amplification from consideration of the radiative transport of energy and entropy. The highest Carnot efficiencies result only when the system is pumped into saturation. In 2002, Bowman and colleagues experimentally demonstrated the first athermal laser (Bowman *et al.* 2002b). Near radiation-balanced operation of the Yb\(^{3+}\):YAG laser with the net thermal loading below 0.01% has been demonstrated in the paper (Bowman *et al.* 2010). Progress on the subject can be found in (Bowman 2016). Several schemes of athermal lasers have been proposed as alternative solutions:

1). **Self-cooling laser**, in which lasing occurs in one system of ions, while anti-Stokes cooling takes place in another system of ions co-doped in the laser host (Andrianov & Samartsev 2001).

2). **Raman lasers with heat mitigation based on CARS**, in which intrinsic heat-mitigation technique relies on coherent anti-Stokes Raman scattering (CARS).

3). Athermal lasers with an integrated cooler

3.1). The athermal Raman fiber laser, in which cooling with anti-Stokes fluorescence in the system of rare-earth (RE) ions compensates for the heat generated inside the active medium due to the quantum defect between the pump and the Raman laser wavelengths (Nemova & Kashyap 2009b, 2009c).

3.2). The athermal RE-doped laser with an integrated cooler, in which lasing takes place in the RE doped fiber core and cooling takes place in the RE doped fiber cladding. The RE doped cladding plays the role of an integrated cooler (Nemova & Kashyap 2010a, 2010b).

References


