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Energy parameters of a self-cooling four-level laser

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***Abstract*.** **The energy balance is considered in a two-impurity, four-level self-cooling laser. It is shown that a self-cooling solid-state laser based on a conventional four-level scheme cannot be built by using traditional active media. Self-cooling can be achieved with the help of new materials or different energy level diagrams.**

Keywords: *laser cooling, solid-state lasers, stimulated emission.*

Recently a number of new studies appeared [1 – 7] devoted to the possibility of building self-cooling solid-state lasers in which a part of radiation energy is used for anti-Stokes cooling of an active laser element [6] by doping it with additional impurity centres. The concept of a two-level self-cooling laser neglecting the heat release upon pumping was proposed in papers [1, 2]. In Refs [3 – 6], the conditions for realisation of a four-level self-cooling laser were analysed taking into account the heat release during transitions only between the upper levels of the four-level energy diagram (Fig. 1a), which is equivalent to the use of a three-level energy diagram. In four-level lasers, heat is mainly released during transitions between the lower levels of the energy level diagram (Fig. 1a). In this paper, we analyse the effect of additional centres of anti-Stokes self-cooling (Fig. 1b) on the energy and spatial characteristics of four-level solid-state lasers.

To determine the energy balance during anti-Stokes self-cooling, we consider the conditions

$$\Delta E_{34} = E_3 - E_4 \simeq E_{A3} - E_{A2} \quad (1)$$

for energy transfer from lasing centres to anti-Stokes-cooling centres,

$$E_4 - E_1 \geqslant 3kT \quad (2)$$

for lasing in the four-level scheme (otherwise, the laser should be considered as quasi-two-level), and

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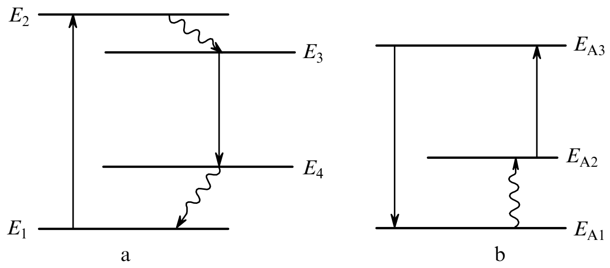

Figure 1. Energy scheme of a self-cooling four-level laser (a) and the energy level diagram of additional anti-Stokes-cooling centres (b).

$$\Delta E_{ast} = E_{A2} - E_{A1} \leqslant 1.5kT \quad (3)$$

for efficient anti-Stokes cooling [7].

In this case, no more than 50 % of energy spent for heating in the idealised four-level laser can be spent for anti-Stokes cooling. We neglect all other heating sources, which appear during the production of population inversion in active centres. Note that because only a relatively small part of the energy of lasing transitions in active centres can be spent for anti-Stokes cooling, the fraction of thermal energy carried away due to anti-Stokes cooling will be even smaller.

The output power of the laser in the case of a homogeneously broadened laser line and optimised transmission of the output mirror is determined, in the Rigrod approximation, by the expression [8]

$$P_{out} = \kappa_0 I_{sat} SL \left[1 - \left(\frac{2\beta L + \delta_{dif}}{2\kappa_0 L}\right)^{1/2}\right]^2, \quad (4)$$

where κ_0 is the gain; I_{sat} is the saturation power; S and L are the cross section and length of the active element; β is the absorption coefficient of the active element related to anti-Stokes centres; δ_{dif} are diffraction losses in the resonator providing the possibility of transverse-mode selection. In the case of efficient anti-Stokes cooling, we have

$$2\beta L > \delta_{dif}, \quad (5)$$

and therefore the selection of transverse modes in the resonator cannot be performed, and the radiation divergence will be determined only by the active substance geometry. In this case, relation (4) takes the form

$$P_{out} = \kappa_0 I_{sat} SL \left[1 - \left(\frac{\beta}{\kappa_0}\right)^{1/2}\right]^2, \quad (6)$$

where the radicand is simply the ratio of the concentration β of anti-Stokes cooling centres to the concentration κ_0 of active centres.

It follows from the conditions considered above that it is difficult to build a self-cooling four-level laser based on conventional materials. Such lasers can be developed by using lasing schemes in which no heat is released upon pumping or by employing materials allowing a large frequency detuning upon cooling. However, this requires further studies.

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