RATE OF RELAXATION FROM THE LOWER LASER LEVEL

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The rate of relaxation of ions from the lower laser level in four-level systems is investigated. The lower limit of the rate of LaF_3—Nd^{3+} is measured and found to be 5×10^4 s^{-1}.

IN processes of stimulated emission in four-level systems an important role is played by the relaxation rate W_{21} of ions from the lower level of the working transition to the ground level, since if this rate is not great enough such effects as saturation and multi-frequency generation appear.[1] Hence it becomes of great practical importance to measure W_{21} in active materials; this is the subject of the present paper.

As was shown in[1], when W_{21} is small the lower laser level is populated when the laser is operating in steady state; hence when the pump is suddenly turned off, generation should not cease immediately but will continue for some time, since the threshold inversion of the populations will be maintained by the decay of the population of the lower laser level. The time behavior of the generation after the pump is turned off is given by the solution of the following system of equations:

$$\begin{aligned}\frac{dn_1}{dt}&=n_2W_{21},\\ \frac{dn_2}{dt}&=-n_2W_{21}+(n_3-n_2)B_{32}u_{32}+n_3W_{32},\\ \frac{dn_3}{dt}&=-n_3W_{32}-(n_3-n_2)B_{32}u_{32},\\ \frac{du_{32}}{dt}&=-\alpha u_{32}+(n_3-n_2)B_{32}u_{32}N_0h\nu,\end{aligned} \tag{1}$$

where $n_i = N_i/N_0$ is the relative density of the population of the i-th level, W_{ij} is the probability of transition from level i to level j, α is a loss coefficient, B_{32} is the Einstein coefficient, u_{32} is the density of radiation in the resonator. As initial conditions we choose the values of the populations and radiation density corresponding to some steady pumping,

$$n_i(t=0)=n_i^{st} \qquad u_{32}(t=0)=u_{32}^{st}\quad .$$

The system of nonlinear equations (1) has under the condition $W_{21} \gg W_{32}$ an approximate solution of the following form:

$$\begin{aligned}n_1&=1-R-\frac{4RB_{32}u}{W_{21}-2W_{32}}e^{-W_{21}t/2},\\ n_2&=\frac{2RB_{32}u}{W_{21}-2W_{32}}e^{-W_{21}t/2},\\ n_3&=\frac{2RB_{32}u}{W_{21}-2W_{32}}e^{-W_{21}t/2}+R,\\ u_{32}&=ue^{-W_{21}t/2},\end{aligned} \tag{2}$$

where $R = (2\alpha - W_{21})/2B_{32}N_0h\nu$. The magnitude of u can be estimated from the condition of equality of the populations before and after pump turn-off, which gives

$$u=u_{32}^{st}\quad \alpha/(2\alpha-W_{21}); \tag{3}$$

when $\alpha \gg W_{21}$, we have $u = u_{32}^{st}/2$.

Thus, the solution of system (1) shows that after pump turn-off the emission of the laser diminishes exponentially with an amplitude equal to one-half the value of the stationary emission. The transition from the stationary emission of the laser to one which decreases exponentially is a typical nonlinear process, and an analytic solution in this region is difficult. As solution of (1) by electronic computer shows, the exponential decay is preceded by rapidly damped oscillations. A graph of the solution is shown in Fig. 1. The estimate (3) for the amplitude u remains valid if the time of decay of the oscillations is much less than the time $1/W_{21}$. The exponential decay of the emission is easy to understand if it is kept in mind that the difference of the populations $\Delta n_{32} = n_3 - n_2$ remains constant, and consequently the density of the field inside the resonator at each moment of time must be such that per unit time half as many particles go from the upper laser level 3 to the lower level 2 as depart from level 2. Thus it is clear that the relaxation time of the emission will be $2/W_{21}$.

In the experiment we used crystals of lanthanum fluoride activated by Nd^{3+} ions (concentration 2 wt.%). Since cw operation has not yet been realized with these crystals, we used a pulsed pump. The pump was turned off by shunting the flashtube with a vacuum discharge. As a result the trailing edge of the pulse was an exponential with decay time $\tau_{off} = 18$ μsec. Figure 2 shows oscillograms of the trailing edge of the pump pulse and of the output radiation of the laser. It is seen that the laser radiation in the trailing edge of the pump pulse has a spiky character, which is evidently due to the emergence of transition processes caused by the relatively slow pump turn-off, as well as to multi-mode generation.

The spiky character of the radiation naturally complicates making an estimate of W_{21}. In spite of this, we have obtained a lower limit of the probability W_{21} based

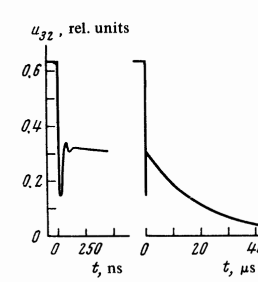

FIG. 1. Time dependence of the output radiation of the laser after the pump is turned off ($W_{21} = 10^5$ sec^{-1}).

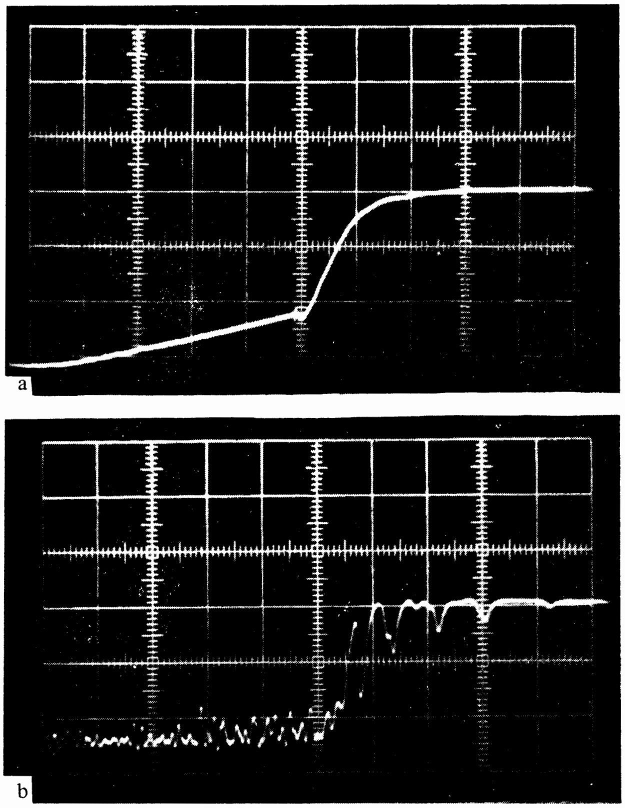

FIG. 2. Oscillograms of the trailing edge of the pump pulse (a) and of laser output (b). Scan 20 μsec/cm.

on an analysis of numerous oscillograms of the decay of the spike amplitude: $W_{21} \geq 5 \times 10^4$ sec^{-1}. A better value can be obtained by decreasing the duration of the trailing edge of the pump pulse. However, the possibilities here are rather limited. Reducing the inductance of the circuit formed by the condensers and the discharge to 3×10^{-8} H does not shorten the time τ_{off}. In this connection, another experiment might be done in which it is possible to be satisfied with the available pump turn-off time. One places a Pockels cell in the resonator which turns on the Q of the resonator after a certain time t_0, where $\tau_{off} < t_0 < \tau$ (τ is the lifetime of the metastable level). Solution of this problem by computer shows that after a giant pulse there follows a

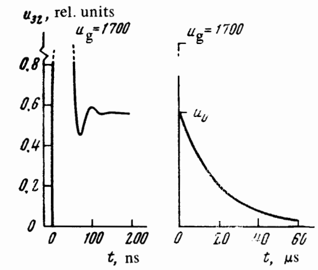

FIG. 3. Time dependence of the laser radiation in the case of simultaneous pump turn-off and Q turn-on ($W_{21} = 10^5$ sec^{-1}).

pulse of radiation with a decay law $u_{32} = u_0 \exp(-W_{21}t/2)$, where $u_0 \sim 10^{-3}u_g$ (see Fig. 3). Obviously, a similar result is obtained if one uses a single-pulse laser as the pump.[2] It should be mentioned that as a consequence of the fact that the lower laser level $^4I_{11/2}$ has six Stark components, the real situation may be more complicated, since instead of one giant pulse there may be several.[3]

It is possible to register, not the pulse of laser radiation, but the pulse of absorption from the excited levels of $^4I_{11/2}$ or $^4F_{3/2}$ of a supplementary light beam passing through the crystal. The pulse of absorption should have an exponentially decaying trailing edge ($e^{-W_{21}t/2}$) corresponding to the decrease of the number of particles in the excited level. Considering that the duration of the giant pulse does not exceed 100 ns, this means of determining the probability W_{21} permits advancing to values of W_{21} equal to about 10^7 sec^{-1}.

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