Coherent effects in the generation and amplification of ultrashort pulses in YAG:Nd and ruby at low temperatures

O. P. Varnavskiĭ, A. N. Kirkin, A. M. Leontovich, R. G. Mirzoyan,
A. M. Mozharovskiĭ, and I. R. Sataev
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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Coherent effects during generation and amplification in YAG:Nd and ruby have been studied at ~100 K for the first time. Intensity oscillations have been observed at the trailing edge of the pulse. The spectrum has a doublet structure. The transverse relaxation time T_2 in ruby is estimated from the decay of the oscillations.

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The coherent interactions of light pulses with resonant media have been studied primarily in absorbing media, where a variety of coherent effects have been observed. There have been only a few experimental studies[1–3] of coherent interactions with amplifying media. These measurements have been carried out in gases with pulses in the nanosecond range. The results generally agree with the results of the far more extensive theoretical papers on the question, but there are many problems, including some of fundamental importance, which remain unresolved because of the paucity of experimental data.[4] In particular, there has been little study of the formation of ultrashort pulses in mode-locked lasers, in which the length of the ultrashort pulses, τ_p, becomes comparable to the phase relaxation time T_2 of the active medium.[5,6] To observe coherent amplification in condensed media is also a problem of undoubted interest. In this letter we report experimental results on generation and amplification of ultrashort pulses in YAG:Nd and ruby at low temperatures, under the condition $\tau_p \lesssim T_2$. Preliminary data on the amplification in YAG:Nd were published in Ref. 7.

The amplification in YAG:Nd is studied on the basis of the transition between the R_1 and Y_1 components of the $^4F^{3/2}$-$4_{I_{11/2}}$ multiplets. We use rods 5×60 and 8×80 mm in size, pumped by flash lamps. The rods are cooled to ~100 K by nitrogen vapor.[8] Estimates of the time T_2^* (the reciprocal of the inhomogeneous width) and T_2 from the spectroscopic data of Ref. 9 yield 20 ps and 150 ps, respectively, for our conditions. The input pulses are produced by the mode-locked YAG:Nd laser described in Ref. 8. The length of these pulses is ~80 ps, their energy is ~1 mJ, and the beam diameter is 2 mm. The pulse shape at the entrance and exit of the amplifier is detected by an electron-optical image-converter camera with a resolving time ~20 ps.

We studied the shape of the pulse at the exit from the amplifier for various areas under the input pulse,

$$\theta = \frac{d}{\hbar} \int_{-\infty}^{\infty} E(t)dt$$

[$E(t)$ is the field amplitude, and d is the matrix element of the dipole moment of the transition.] For an input area ~0.5π and a weak-signal gain $\alpha L \sim 5$, we observed

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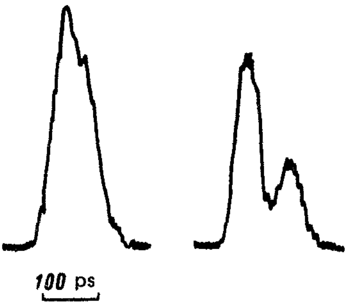

FIG. 1. Densitometer traces at the entrance and exit (left and right, respectively) of a YAG:Nd amplifier at $\theta \sim 0.5\pi$.

the characteristic splitting of the pulse at the exit from the amplifier.[1,10] Figure 1 shows a densitometer trace of the output. In several cases, we observe a third, small-amplitude surge on the trailing edge after back-and-forth traversal of the amplifier. When the area under the input pulse is reduced, the splitting becomes more noticeable, and at $\theta < 0.2\pi$ the shapes of the pulses at the entrance and exit are identical. The pulse splitting also disappears when the rod temperature is raised, at any attainable θ.

Figure 2 shows the spectrum of the amplified pulse. We see the characteristic doublet structure, which may be interpreted as the result of dynamic Stark splitting in the field of the amplified signal. These results agree well with the results of a numerical calculation carried out for conditions corresponding to our experiments.[10]

At a given shape and intensity of the input pulse, the splitting is not always observed. In particular, it does not occur if the input pulse is amplified beforehand in neodymium glass to a high intensity. It may be that this result is due to a phase modulation of the input pulse, which varies from shot to shot, as was found in preliminary measurements. On the other hand, this result, when combined with a temperature dependence, confirms that the splitting of the pulse is not a consequence of self-focusing.

The coherent effects should obviously be manifested in the resonator of the generator of the ultrashort pulses in the later stage of the generation if the active medium

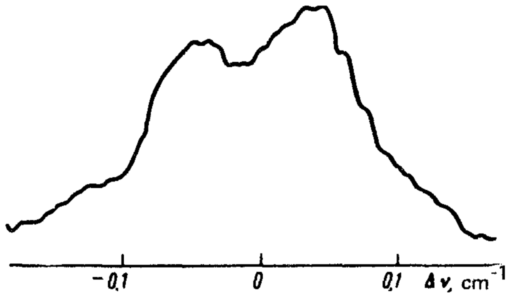

FIG. 2. Spectrum of a pulse amplified in the YAG:Nd.

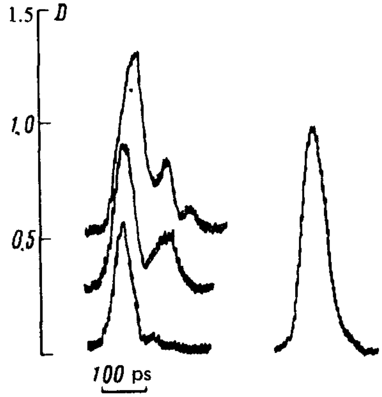

FIG. 3. Densitometer traces of the pulses from a mode-locked ruby laser. Left—Medium temperature ~100 K (the curves correspond to three successive degrees of attenuation at the entrance slit of the chamber); right—medium temperature ~190 K. D is the blackening.

has a sufficiently long T_2. In fact, splitting of the pulse sometimes occurred even in the output from the YAG:Nd laser at a low temperature, at the maximum of the train of the ultrashort pulses. The effect is seen more clearly, however, in the ruby generator at ~100 K. The coherent nature of the interaction of the ultrashort pulses with the ruby at low temperatures was established in Refs. 11 and 12, where we observed a self-induced transparency and a coherent amplification.

We studied ultrashort pulses generated in a ruby laser with mode locking at ~100 K. We use an unstable resonator with a glass substrate as an output mirror. The laser generates a train of two or three ultrashort pulses with a total energy of 150–200 mJ and a maximum pulse energy up to 50–100 mJ. The pulse length is typically 40–50 ps; the beam diameter in the active rod is 4–6 mm. The maximum pulse in such a resonator can be regarded as the result of an amplification in a single pass through the resonator. Figure 3 shows a densitometer trace of the output in the highest pulse in the train. We can clearly see oscillations on the trailing edge of the pulse. Shown for comparison is a trace obtained at an active-medium temperature ~190 K. In this case there are absolutely no oscillations.

From the appearance of the oscillations with decreasing temperature or decreasing pulse length we can estimate T_2, which is an important spectroscopic parameter of the medium. For ruby at 100 K, for example, we find $T_2 \sim 150$ ps, while at 190 K we find $T_2 \lesssim 60$ ps.

To the best of our knowledge, there has been no previous study of coherent effects during the generation and amplification of picosecond pulses in condensed media.

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