Change in the shape of a weak, ultrashort light pulse passing through a medium with a population inversion and a slow phase relaxation

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(Submitted 16 October 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 1, 9–11 (10 January 1985)

The change in the shape of weak, ultrashort light pulses during a coherent interaction with an amplifying medium has been studied. Shape changes were detected even when the effect of the pulses on the level populations was negligible. These changes are linked with an emission due to a macroscopic polarization produced in the medium by the initial pulse.

The evolution of light pulses passing through a medium with a population inversion and a slow phase relaxation is quite different from that in the case of ordinary incoherent amplification, in which case the phase-relaxation time of the medium, T_2, is shorter than the pulse length τ_p (Ref. 1). The phase memory of the medium causes the local polarization at each instant to be determined by the time dependence of the field in the medium over an interval on the order of the phase-relaxation time. This polarization, in turn, affects the nature of the interaction of the light with the medium. In particular, the amplification or absorption of the light is determined not by the population inversion for the transition but by the relative phases of the field and the polarization.

Consequently, under the condition $\tau_p < T_2$, even for weak signals which do not substantially change the level populations for the amplifying transition, we should see

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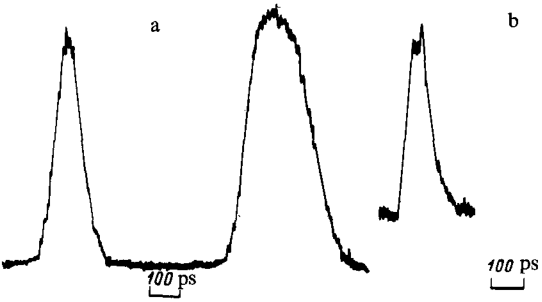

FIG. 1. Densitometer traces of the pulses from a ruby laser before (left) and after (right) amplification in a ruby crystal at 80 K. The vertical scales are arbitrary for both pulses.

some features not found in the incoherent regime. For weak pulses with $\tau_p < T_2$, for example, there is a deviation from Beer's law, and the signal increases in accordance with $\exp\sqrt{\beta x}$ ("lethargic amplification"[2,3]). In the present letter we report an experimental study of the change in the shape of pulses during amplification in a medium with a slow phase relaxation. In contrast with Ref. 1, where we studied the distinctive features of the coherent amplification of intense pulses, in the present case we studied pulses which have a negligible effect on the level populations. To the best of our knowledge, there has been no previous study of this type for media with a population inversion.

As a model medium we use ruby (the R_1 line) at $\cong 80$ K ($T_2 \cong 300$ ps). The output pulse from a ruby laser with mode self-locking is applied to the entrance of an amplifying element 12 cm long with a single-pass gain $\cong 500$ (for a weak pulse lasting longer than T_2). The pulse is first passed through a saturating filter and attenuated by neutral filters. As the pulse passes through the saturating filter, the oscillations on the trailing edge of the pulse detected in Ref. 1 are suppressed. The pulse at the entrance to the amplifier is structureless and has a length of 30–50 ps. The ruby crystals in the laser and the amplifier are cooled with liquid nitrogen. An image converter with a resolution $\cong 20$ ps is used as a detector.

Figure 1 shows densitometer traces of photographs from the screen of the image converter. The areas under the input pulses are $\pi/200$. The peak power of the light increases by a factor of only $\cong 10$ in the amplifier. The areas under the output pulses do not exceed $\pi/20$; i.e., the change in the level populations can be ignored. In each case the pulses lengthen to 250–300 ps, corresponding approximately to T_2. As the temperature of the amplifying crystal is raised, the length of the output pulse decreases. At 100 K, this length is 100–150 ps, again corresponding to T_2.

The observed elongation of the pulses is apparently due to an emission caused by a macroscopic polarization produced in the medium by the initial pulse. A related effect was observed in an absorbing medium by Hartman and Lauberau,[4] who detected a broadening of a small-area pulse in an extended medium. This result is also attributed to a coherent emission due to a macroscopic dipole moment which is induced in the medium and which is damped over a time $\cong T_2$.

In the experiments with short input pulses, we frequently observed the appearance of a structure with a central dip (Fig. 1b). This result can be explained as follows.

The kinetics of the emission in our case is similar to that of cooperative spontaneous emission (Dicke superradiance[5]). In contrast with superradiance, however, the dipole moments of the various atoms do not come into phase spontaneously but under the influence of the field of the short, weak pulse.

According to MacGillivray and Feld,[6] the buildup of the superradiance pulse is delayed

$\tau_D \cong \tau_R \mid \ln \theta_0 / 2\pi \mid^2$

with respect to the time at which the population inversion occurs. Here τ_R is the superradiance scale time, and θ_0 is the initial polar angle of the Bloch vector. If θ_0 is determined not by spontaneous fluctuations of the polarization but by a small-area nucleating pulse, then the time of arrival of the nucleating pulse should be adopted as the reference point. This regime was studied theoretically by Milikov and Trifonov,[7] who called it "induced superradiance." It may be assumed that if the input pulse is shorter than τ_D then two pulses will appear at the exit from the amplifying medium. The first pulse will correspond to the amplified input pulse, and the second to a light pulse caused by the dipole moment induced in the medium by the first pulse. In the case $\tau_p > \tau_D$, the pulse emitted by the medium should be superimposed on the input pulse, increasing its length to $\cong T_2$. In this case a smooth, structureless pulse will be observed at the exit.

In our case we have $\tau_D \cong 50$ ps, so that the structure of the output pulse in Fig. 1b can be attributed to the satisfaction of the condition $\tau_p < \tau_D$, although, strictly speaking, the condition $\tau_p < \tau_R$ would have to be satisfied for a realization of the pure, induced superradiance.[7] Furthermore, we do not rule out the possibility that the development of structure in the output pulse is promoted by the formation of a coherent superposition of two sublevels of a low-lying state of a chromium ion in the ruby. The oscillation period corresponding to the frequency interval between these sublevels is $\cong 40$ ps.

Measurements were also carried out without the saturable filter at the output from the laser oscillator. In this case the input pulse had an oscillatory structure due to coherent amplification; as we have shown previously,[1] the phase of the field changes abruptly by π in each successive oscillation. Figure 2 shows densitometer traces for an input pulse with an area $\cong \pi/20$ and an oscillatory structure. The pulse length is greater than the delay time τ_D, so that the light pulse due to the induced moment is

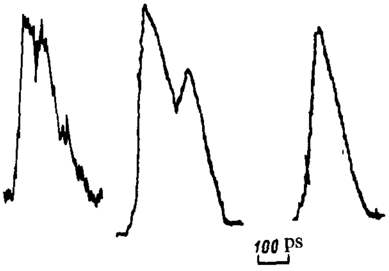

FIG. 2. The same as in Fig. 1, but the input pulse has an oscillating envelope.

superimposed on the input pulse and interferes with it. The interference within the first oscillation of the envelope is constructive, as in Fig. 1a, while that in the second oscillation of the envelope is destructive. There is accordingly a suppression of the oscillations on the trailing edge of the original pulse.

In summary, under the conditions of a coherent interaction, there is a change in the shape of a light pulse, even if this pulse is too weak to have any significant effect on the population inversion. This effect might be exploited to shape pulses during coherent amplification.

We thank M. D. Galanin and A. M. Leontovich for their time and interest, and we thank R. F. Malikov and E. D. Trifonov for useful discussions.

[1] O. P. Varnavskiĭ, A. N. Kirkin, A. M. Leontovich, *et al.*, Zh. Eksp. Teor. Fiz. **86**, 1227 (1984) [Sov. Phys. JETP **59**, 716 (1984)].
[2] M. D. Crisp, Phys. Rev. **1A**, 1604 (1970).
[3] H. K. Chung, J. B. Lee, and T. A. DeTemple, Opt. Commun. **39**, 105 (1981).
[4] H. -J. Hartman and A. Lauberau, Opt. Commun. **47**, 117 (1983).
[5] R. H. Dicke, Phys. Rev. **93**, 99 (1954).
[6] J. C. MacGillivary and M. S. Feld, Phys. Rev. **14A**, 1169 (1976).
[7] R. F. Milikov and E. D. Trifonov, Opt. Commun. **52**, 391 (1984).

Translated by Dave Parsons
Edited by S. J. Amoretty