Superradiance of two-component media

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The intensity of a superradiance pulse in a two-component medium may be significantly higher than that for each component separately. The delay time may be several orders of magnitude longer, which would substantially relax the requirements on the length of the pulse.

1. Superradiance theories have customarily been based on the assumption that all the atoms are initially excited and that the field is in a vacuum state.[1–5] This assumption means that the atoms are excited instantaneously, i.e., that the pump pulse is a δ-function pulse. Studies of the effect of a finite duration of the pump pulse on the parameters of superradiance pulses have been stimulated by experimental studies of the effect.[6–9] They have shown that, when the length of the pump pulse begins to approach the length of the superradiance pulse in the case of instantaneous pumping, the superradiance pulse begins to broaden and change in shape. In the standard laser layouts, the requirements on the length of the pump pulse are relaxed by using various types of Q switching.[10] Since superradiance is a cavity-free generation, however, these layouts cannot be applied directly to the case of superradiance.

In the present letter we show that the superradiance of a two-component medium differs in a qualitative way from conventional superradiance. In particular, under certain conditions there may be a substantial increase in the delay time and a decrease in the length of the superradiance pulse. It then becomes possible to relax the requirements on the length of the pump pulse and at the same time increase the intensity of the superradiance.

2. Let us assume that an active medium consists of two components, a "slow" one and a "fast" one (the resonant-absorption cross section for the fast component, σ_b, is much larger than that for the slow one: $\sigma_a \ll \sigma_b$). Let us examine the evolution of this system in a coherent regime in which the time scale for the uniform relaxation of each component is much longer than the length of the pulse generated by the medium. The fast medium is initially in the ground state. The external pump sources excite the slow component into the upper level of a resonant transition.

Here is the system of equations for the slowly varying amplitudes of the counterpropagating waves ($a_{1,2}$) and of the polarization waves ($q_{1,2}$) ($p_{1,2}$ are the polarizations) for the slow (fast) component and the population inversion r_1 (r_2):

$$\frac{\partial a_1}{\partial t}+c\frac{\partial a_1}{\partial x}=p_1+q_1+p_0(1+r_1)+q_0(r_0+r_2),$$

$$\frac{\partial a_2}{\partial t}-c\frac{\partial a_2}{\partial x}=p_2+q_2+p_0(1+r_1)+q_0(r_0+r_2),$$

$$\frac{\partial p_{1,2}}{\partial t}+\alpha_1 p_{1,2}=\beta_1 a_{1,2} r_1 ,$$

$$\frac{\partial p_{1,2}}{\partial t}+\alpha_2 q_{1,2}=\beta_2 a_{1,2} r_2 ,$$

$$\frac{\partial r_1}{\partial t}=-(a_1 p_1+a_2 p_2)+F,\quad \frac{\partial r_2}{\partial t}=-(a_1 q_1+a_2 q_2). \qquad (1)$$

Here we have introduced the dimensionless time $t=t'/\tau$ and the dimensionless coordinate $x=x'/L$, where L is the length of the medium, and $\tau=L/c$. The amplitudes $a_{1,2}$ have been normalized in such a way that the quantities $n_{1,2}=|a_{1,2}|^2$ are the number densities of photons in units of the number density of the atoms of the slow component, $n_a=N_a/V$. The population-difference densities $r_{1,2}$ are normalized to n_a. The quantity r_1 thus has the range $-1<r_1<1$, and the initial value of r_2, i.e., $r_2(x,0)=-n_b/n_a$, specifies the ratio of the densities of fast and slow atoms. The dimensionless rates of uniform relaxation are given by

$$a_{1,2}=\tau/T_2^{(a,b)}, \qquad (2)$$

and the coefficients $\beta_{1,2}$ are

$$\beta_{1,2}=\frac{2\pi\omega_0|d_{a,b}|^2\tau^2}{\hbar}n_a .$$

The last two terms on the right side of the first two equations of system (1) describe sources of spontaneous polarization, while $F(x,t)$ in the equation for r_1 is the pumping rate

$$F(x,t)=F_0\exp[-(t-t_0)^2/\tau_p^2], \qquad (3)$$

where $F_0\tau_p\sqrt{\pi}=1$.

The initial conditions are

$$a_{1,2}(x,0)=p_{1,2}(x,0)=q_{1,2}(x,0)=0,$$
$$r_1(x,0)=0,\quad r_2(x,0)=-r_0 . \qquad (4)$$

Figure 1 shows how the profile of the superradiance pulse of a single-component medium (with $a_1=0.01$ and $\beta_1=1$) evolves with increasing length of the pump pulse. We see that the pulse height decreases with increasing τ_p, while the pulse length increases. Figure 2 shows the transformation of the profile of the superradiance pulse of a two-component medium (with $\alpha_1=0.01$, $\beta_1=1$, $\alpha_2=0.1$, $\beta_2=15$ and with a pump pulse length $\tau_p=100$) as the concentration of the fast component increases.

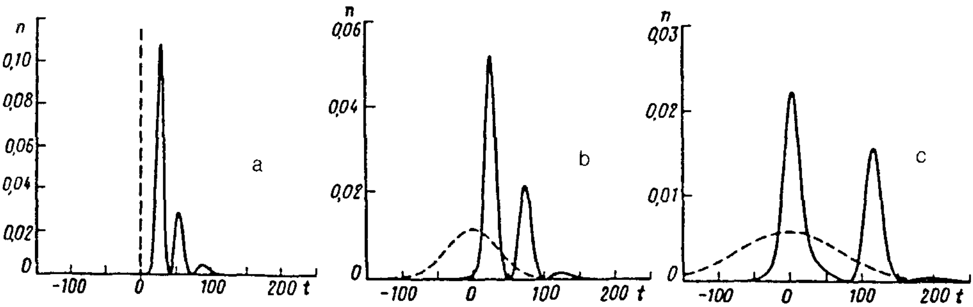

FIG. 1. Profile of a superradiance pulse of a single-component medium ($\alpha_1=0.01, \beta_1=1, r_0=0$) for various lengths of the pump pulse. a—$\tau_p=0$; b—50; c—100.

With increasing r_0, there is an increase in the pump delay time, the pulse becomes shorter, and the peak intensity increases. At $r_0=0.13$, the profile of the superradiance pulse for a single-component medium with instantaneous pumping is reproduced (Fig. 1a). With a further increase in r_0, the intensity of the generation pulse begins to exceed that of the superradiance pulse for the slow component with instantaneous pumping. Figure 3 shows the resultant curve of the peak intensity versus the concentration of the fast component, r_0. Dashed line 1 shows the peak intensity of the superradiance for a single-component medium consisting of slow atoms with instan-

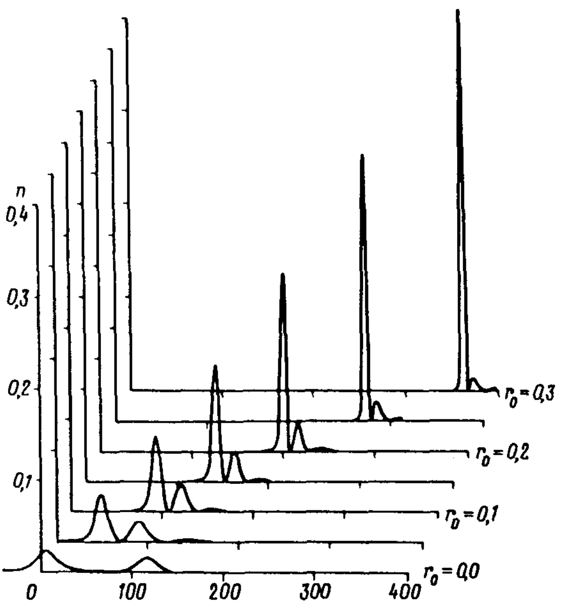

FIG. 2. Profile of the superradiance pulse of a two-component medium (with $\alpha_1=0.01, \beta_1=1, \alpha_2=0.1, \beta_2=15$ and with a pump pulse length $\tau_p=100$) for various concentrations of the fast component, r_0.

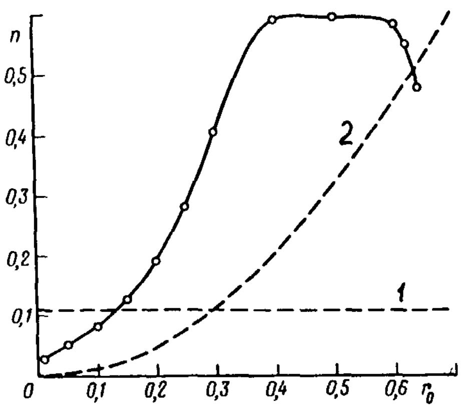

FIG. 3. Peak intensity of the superradiance pulse of a two-component medium (with $\alpha_1=0.01$, $\beta_1=1$, $\alpha_2=0.1$, $\beta_2=15$ and with a pump pulse length $\tau_p=100$) versus the concentration of the fast component.

taneous pumping. Dashed line 2 shows the peak intensity of the superradiance as a function of the number density of atoms for a medium consisting of the fast component. At $0.13\leqslant r_0\leqslant 0.63$ the superradiance intensity of a two-component medium exceeds that for each of the components separately, and the profile of the pulse is such that much of the radiant energy is within the first peak.

3. This study has shown that the use of two-component superradiant media opens up new possibilities for controlling the parameters and shape of the pulses which are generated. By varying the concentration of the components and the length of the active medium, one can control the space-time dynamics of the generation. This capability makes possible a substantial increase in the intensity of the superradiance pulse and a simultaneous increase in the delay time.

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