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# Cooperative Effects in Quartz Media with Quantum Dots

A.V. Pishenko[1], M.G. Gladush[2], and A.V. Prokhorov[1a]

[1]*Vladimir State University, 600000, Vladimir, Gorky str., 87,*
[2]*Institute for Spectroscopy of RAS, 142190, Russia, Troitsk, Moscow, Fizicheskaya str., 5*

**Abstract.** We theoretically consider a problem of generation of infrared pulses of superradiation (SR) in a dielectric medium hosting a dense ensemble of quantum dots produced using the narrow gap semiconductors. We have studied the influence of complex local-field corrections on cooperative optical processes in such a material due to essential modifications of the effective values of the spontaneous relaxation rates.

The first experiments with optical SR in solids [1] revealed essential differences of this effect in comparison with gas medium [2] that was caused by short distances between the defect centers and influence of the host medium on the properties of individual quantum emitters. Some special interest is expected towards the studies of SI-pulse generation in dense ensembles of quantum emitters with resonant frequency which is overlapped by the wing of profile of the absorption line of the host medium. This task is conditioned by new technical possibilities regarding receiving optically-transparent medium doped by quantum dots [3]. Due to existence of high-valued transition dipole moment $\mu$ of quantum dots it is possible to reduce significantly the duration of the characteristic SR time $t_R = \sqrt{2\hbar\varepsilon_0/\omega\mu^2 N_a}$ ($\omega$ is the frequency of electronic transition, $N_a$ is concentration of radiators) and to observe generation of extremely short and powerful impulses of superradiation. Additional control of dynamics of such processes is connected with the use of dimensional effects for quantum dots [4,5]. In this work we consider a problem of formation of infrared SR pulses which are generated by ensembles of semiconductor quantum dots in the quartz host medium. The model of generation is based on system of the equations for density matrix elements:

$$\dot{\rho}_{11} = -i\left(\Omega_0\rho_{12} - \Omega_0^*\rho_{21}\right) + 2\xi_0 u_I\left|\rho_{12}\right|^2 + \Gamma_\varepsilon\rho_{22}, \tag{1.a}$$

$$\dot{\rho}_{12} = i\left(\Omega_0^* + \xi_0 u_R\rho_{12}\right)\left(\rho_{22} - \rho_{11}\right) - i\Delta_\varepsilon\rho_{12} + \xi_0 u_I\left(\rho_{22} - \rho_{11}\right)\rho_{12} - \frac{\Gamma_\varepsilon}{2}\rho_{12}, \tag{1.b}$$

$$\dot{\rho}_{21} = -i\left(\Omega_0 + \xi_0 u_R\rho_{21}\right)\left(\rho_{22} - \rho_{11}\right) + i\Delta_\varepsilon\rho_{21} + \xi_0 u_I\left(\rho_{22} - \rho_{11}\right)\rho_{21} - \frac{\Gamma_\varepsilon}{2}\rho_{21}, \tag{1.c}$$

$$\dot{\rho}_{22} = i\left(\Omega_0\rho_{12} - \Omega_0^*\rho_{21}\right) - 2\xi_0 u_I\left|\rho_{12}\right|^2 - \Gamma_\varepsilon\rho_{22}, \tag{1.d}$$

where the Rabi frequency $\Omega_0 = g\varepsilon'\cdot\sqrt{l_R^2 + l_I^2}$ is expressed through a coupling constant $g = \mu_{12}\sqrt{\omega/2\hbar\varepsilon_0 V}$ and a normalized field $\varepsilon = A_p\left(2\varepsilon_0 V/\hbar\omega\right)^{1/2}$ with the amplitude

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[a] Corresponding author: avprokhorov33@mail.ru

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$A_p = \sqrt{I_p / C_0}$ and $C_0 = c\varepsilon_0 / 2n_R$. Dispersive $u_R = (l_R\varepsilon_R + l_I\varepsilon_I)/(\varepsilon_R^2 + \varepsilon_I^2)$ and dissipative $u_I = (l_I\varepsilon_R - l_R\varepsilon_I)/(\varepsilon_R^2 + \varepsilon_I^2)$ coefficients are expressed through the real $\varepsilon_R$ and imaginary $\varepsilon_I$ parts of dielectric permeability of the host medium and it arise in (1) because of the accounting of the local field corrections. Expressions for effective value of the rate of spontaneous relaxation $\Gamma_\varepsilon$ and detuning frequencies $\Delta_\varepsilon$ in the host medium with complex refractive index $n = n_R + in_I$ can be presented as $\Gamma_\varepsilon = \Gamma_a\left(n_R l_R - n_I l_I + \frac{2\Delta_a}{\Gamma_a} l_I\right)$ and $\Delta_\varepsilon = \Delta_a\left(l_R - \frac{\Gamma_a}{(2\Delta_a)(n_I l_R + n_R l_I)} l_I\right)$. Here $\Delta_a$ is the optical detuning, $\Gamma_a$ is the rate of spontaneous relaxation of emitters in the vacuum. The task (1) is supplemented with the equation for the Rabi frequency of effective (Lorenz) field:

$$\Omega_0 = -\frac{i}{\tau_R^2}\rho_{12}, \tag{2}$$

and it can be solved in the approximation of a thin layer [6] dielectrics with quantum dots.

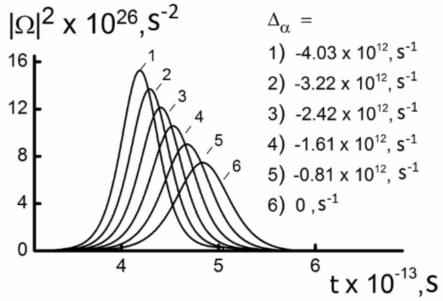


**Figure 1.** Profiles of SR pulses at various parameters for quantum dots of PbSe in the dielectric $SiO_2$ medium. Radius of quantum dots $a = 33.5$ nm, wavelength of radiation and the dipolar moment of transition are equal $\lambda_a = 6.5\,\mu m$ and $\mu = 23.2 \cdot 10^{-28}\, C \cdot m$, respectively; $\Gamma_a = 5 \cdot 10^{11}\, s^{-1}$, $N_a = 1.8 \cdot 10^{21} m^{-3}$.

The analysis of the self-consistent problem (1)-(2) showed essential dependences of SR pulse parameters on dispersive and dissipative local-field corrections, including the characteristic SR times, duration of pulses, its form and the area. In particular, at the condition of $\Delta_a = 0.5 \cdot \Gamma_a \cdot l_I^{-1} \cdot (n_I l_I - n_R l_R)$ the spontaneous relaxation rate in such medium can be completely nullified that corresponds to profile 1 in fig. 1. Thus, the shift from these conditions leads to the increase of the contribution of the incoherent processes with reduction of power of the generated SR pulses up to their full suppression. Other features of the system (1)-(2) is the possibility control the spectrum of the formed SR pulses in the considered medium.

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