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Dynamics of phonon mode in superradiance regime of laser cooling of crystals

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Abstract

The kinetics of the impurity crystal in regime of anti-Stokes laser cooling has been considered taking into account the collective radiation effects. The system of master equations for impurities and pseudo-local phonons has been obtained. As would be expected, the collective radiation effects causes an acceleration in relaxation depletion of the phonon mode and therefore an increase of crystal cooling efficiency.

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Keywords: Laser cooling of solids; Anti-Stokes radiation; Superradiance

1. Introduction

Laser cooling of solids is one of the most important problems in laser physics in the context of the practical demand to build up compact highly efficient solid laser refrigerators operating without cryogenic liquid [1,2]. As one of the more effective system to produce laser cooling, the rare-earth ions in transparent solids has been suggested by Kastler [3]. In 1995, Epstein et al. [4] used rare-earth ions of (Yb^{3+}) in heavy-metal fluoride glass to perform a realible experiment on laser cooling. The effect of laser cooling has been archived by use of the anti-Stokes fluorescence regime when the pumping quantum is less than the fluorescence quantum by the phonon energy. The theory of the anti-Stokes regime of laser cooling in solids has been developed in the framework of the model of pseudo-local phonon modes in series of papers of Samartsev with collaborators (see [5,6] and references wherein) with using the different methods of nonequilibrium statistical mechanics. The superradiance regime of

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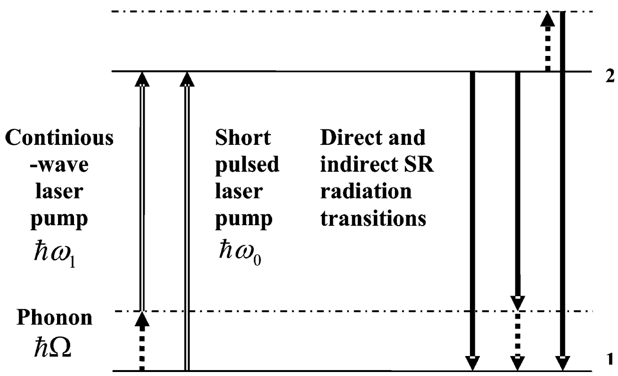

Fig. 1. Scheme of energy levels and transitions in two-level impurity ion in the superradiance regime of laser cooling. 1 and 2 are the ground and excited states of ion, $\hbar\omega_1$ is the energy of continuous-wave laser pump quantum, $\hbar\omega_0$ is the energy of pulsed laser pump quantum, $\hbar\Omega$ is the energy of phonon.

laser cooling of crystals doped with rare-earth ions has been proposed by Petrushkin and Samartsev [7] to increase the efficiency of laser cooling. Note that since 1982 the superradiance in solids has been the subject of intensive experimental investigations [8,9]. In 1999 superradiance was detected in experiments performed with rare-earth ions [10]. The authors of [7] have focused main attention on radiative processes and excluded the dynamics of phonons transitions from consideration. However, the analysis of phonons dynamics is most useful to perform the evaluation of a superradiance processes on efficiency of laser cooling in solids. And the main aim of our Letter is to present such analysis on the basis of the Bogolubov method of elimination of the boson variables (see, for instance, [11]).

Let us consider following the paper [5] an ensemble of N two-level ions in molecular crystal with resonance frequency ω_0 interacting with quantum electromagnetic field on direct transitions 1–2 (see Fig. 1) and two coherent pumping fields—the continuous-wave laser radiation with frequency ω_1 obeying the condition $\omega_1 < \omega_0$ and the pulsed short laser radiation with frequency ω_0. The impurity ions interact also with pseudo-local phonon mode with frequency Ω. The pseudo-local phonons are due to anisotropic ions vibrational librations with respect to their equilibrium positions in crystal. These librations modulate the constant of ion–photon interaction which gives rise to the indirect transitions, when a phonon is absorbed or emitted simultaneously with photon. Continuous-wave pumping laser radiation with frequency $\omega_1 = \omega_0 - \Omega$ excites two-level ions from state 1 to state 2 with simultaneous absorption of a phonon with frequency Ω. These transitions and indirect anti-Stokes transitions 2–1 accompanied by decreasing of phonons number in pseudo-local mode. On the contrary the indirect Stokes transitions 2–1 result in the emission of the phonons. The direct spontaneous relaxation 2–1 do not vary the phonons quantity. The cooling takes place as long as the number of absorbed phonons exceeds the number of emitted phonons in a unit of time because the decreasing of phonons number leads to lowering of effective temperature of the pseudo-local phonon mode. The temperature of the whole-sample through the energy exchange between the phonon modes is lowered too. The pulsed laser radiation is necessary for realization the superradiance regime of cooling.

2. Model Hamiltonian

The Hamiltonian of the system under consideration can be written as

$$H = H_A + H_F + H_{AF}, \tag{1}$$