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SEMICLASSIC MODELS OF THE DISSIPATIVE REGIME OF INSTABILITY AND SUPERRADIATION OF A QUANTUM RADIATOR SYSTEM

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The paper discusses the similarity between dissipative generation and superradiance regimes for systems of excited quantum emitters placed in an open cavity. In the case of the existence of a resonator field due to reflections from the ends of the system, a dissipative generation regime is usually realized. In this case, the decrement of oscillations in the waveguide in the absence of radiators turns out to be greater than the increment of the arising instability of the system of radiators placed in the resonator. When describing this mode, the influence of the emitters on each other and the sum of their own fields is neglected. The resonator field forces the oscillators to emit or absorb quanta synchronously with it, depending on the local value of the population inversion. Lasing takes on a weakly oscillatory character due to an asynchronous change in the population inversion of the system of emitting dipoles (nutations), which have a ground and excited energy levels. To describe the process, the equations of the semiclassical theory based on the use of the density matrix are quite sufficient. In the case when there is no resonator or waveguide field, taking into account the eigenfields of the oscillators becomes essential. To simulate the superradiance process, large emitting particles are used, to describe which one should use the equations for the density matrix. It is shown that the interaction of quantum emitters in this case is due to electromagnetic fields under conditions when the overlap of their wave functions is insignificant. Equations are obtained that allow considering the process of interaction of emitters. When the emitters interact, an integral field is formed in the resonator, an increase in the intensity of which leads to synchronization of the emitters. It is shown that the characteristic times of the development of the process, as well as the attainable amplitudes of the excited fields for dissipative regimes of generation and regimes of superradiance of emitters filling an open resonator, are comparable.
KEYWORDS: dissipative regimes of generation, superradiance, open resonator.

In the well-known work [1] R. Dicke, considering the interaction of oscillators or emitters, which are actually combined into one quasiparticle, discovered the possibility of their coherent radiation. Moreover, in the quantum case, we can talk not about the phase synchronization of the oscillators, as in the classical consideration, but only about an increase in the probability of radiation, which actually leads to the same result. The overlap of their wave functions leads to an increase in the probability of spontaneous emission of this quasiparticle in comparison with the probability of emission of individual oscillators or emitters[1] [2].

If the oscillators or emitters are separated in space, the overlap of their wave functions becomes imperceptible[2]. The interaction of quantum emitters in this case is due to electromagnetic fields. In this case, the Rabi frequency determines the oscillatory nature of the change in the population inversion of the system of emitting dipoles (nutations), which have a ground and excited energy levels. The probabilities of stimulated emission and absorption of field quanta are also determined by the Rabi frequency [3].

In open systems, when the reflection of waves from the boundaries of the system is weakened, dissipative generation modes and superradiance modes can be realized [2, 4-8].

A resonator or waveguide field, the intensity of which is sufficiently high in the case of low energy losses, is formed due to reflections from the ends of the system. In this case, the influence of emitters on each other can often be neglected. The field of the resonator or waveguide forces some of the oscillators to emit and absorb quanta synchronously with it, providing a significant coherence [9]. This stimulated emission usually exceeds the sum of incoherent emitters eigenfields; therefore, taking them into account in such a regime of instability development is often insignificant.

In the superradiance mode, a resonator or waveguide field may not be present in the system of oscillators, since these modes are realized in open systems with weak reflection of the excited oscillations from the ends of the system. In a quantum system, at large values of the number of excited oscillators and their tight localization, spontaneous emission at a high density of emitters remains, as a rule, extremely insignificant in relation to the radiation induced.

Usually, in the absence of a resonator or waveguide field, the total field of such spontaneous electromagnetic emission very large number of particles of the active substance (which emit only one quantum in a rather arbitrary chaotic manner) is inversely proportional to their number and not able to synchronize them. However, with the use of an initiating external field capable of synchronizing the emitters, the superradiance regime may well be realized. If the number of emitters is small, the levels of the total spontaneous electromagnetic radiation may be sufficient to form an integral field that synchronizes the emitters, as shown below. In open systems, with a sufficiently high level of radiation from the ends

1 That is, the coherence of radiation of a bunch of particles, the size of which is much smaller than the wavelength, is found both in the quantum description of this phenomenon and in the classical one.
2 The velocity distribution of free electrons in semiconductors is indicative in this sense [9].

of the system, both a dissipative excitation mode of a waveguide or resonator field by non-interacting with each other emitters, and a superradiance mode of the system, when there is no waveguide field, and each emitter participates in creating a sufficiently intense integral field, are possible.

The aim of this work is to consider the features of dissipative generation regimes and superradiance regimes for systems of excited quantum emitters placed in an open resonator.

This is first of all comparison of the characteristic times of these processes, as well as the attainable amplitudes of the excited fields. The similarity of the superradiance regimes and dissipative regimes of generation of quantum oscillators is shown in this case.

DESCRIPTION OF GENERATION PROCESSES BY A SYSTEM OF QUANTUM EMITTERS

Thus, it is rational to consider the behavior of emitters in a quantum-mechanical way, and the field - in the classical representation. Below, we will consider the behavior of quantum emitters, the wave functions of which do not overlap and their interaction is determined only by the electromagnetic field. In this case, a semiclassical description model based on the use of a density matrix is applicable. Neglecting relaxation processes, the equations for the components of the density matrix can be written in the form

$$\frac{d}{dt}(\rho_{aa}-\rho_{bb}) = -\frac{2i}{\hbar}[d_{ba}\rho_{ab} - d_{ab}\rho_{ba}]E\,, \tag{1}$$

$$\frac{d}{dt}\rho_{ab} + i\omega_{ab}\rho_{ab} = -\frac{i}{\hbar}(\rho_{aa}-\rho_{bb})d_{ab}E\,, \tag{2}$$

where the electric field is represented in the form $E + E^* = A(t)\cdot\exp\{-i\omega t\} + A^*(t)\cdot\exp\{i\omega t\}$, and the rapidly changing polarization of one emitter has the form $d_{ba}\rho_{ab} + d_{ab}\rho_{ba}$. From $\rho_{ab} = \overline{\rho}_{ab}e^{-i\omega_{ab}t} = \overline{\rho}_{ab}e^{-i\omega t}$ let us determine slowly changing quantities for the polarization of the emitter $\overline{p} = d_{ba}\cdot\overline{\rho}_{ab}$ and $d_{ab}\overline{\rho}_{ba} = d^*_{ba}\,\overline{\rho}^*_{ab} = \overline{p}^*$ also write down the system of equations for the inversion of one emitter $\overline{\mu} = (\rho_{aa}-\rho_{bb})$ and $\overline{p}$:

$$\frac{d}{dt}(\rho_{aa}-\rho_{bb}) = -\frac{2i}{\hbar}[d_{ba}\overline{\rho}_{ab}A^* - d_{ab}\overline{\rho}_{ba}A] = -\frac{2i}{\hbar}[\overline{p}A^* - \overline{p}^*A]\,, \tag{3}$$

$$\frac{d}{dt}\overline{p} = -\frac{i}{\hbar}(\rho_{aa}-\rho_{bb})\,|\,d_{ba}\,|^2\,A\,. \tag{4}$$

Using these representations, one can obtain equations for the semiclassical model. In the one-dimensional case, which we restrict ourselves to, for perturbations of the electric field E, polarization P, and population inversion slowly varying with time μ, describing the excitation of electromagnetic oscillations in a two-level active medium, whose equations can be represented as (see, for example, [11, 12])

$$\frac{\partial^2 E}{\partial t^2} + \delta\frac{\partial E}{\partial t} - c^2\frac{\partial^2 E}{\partial x^2} = -4\pi\frac{\partial^2 P}{\partial t^2}\,, \tag{5}$$

$$\frac{\partial^2 P}{\partial t^2} + \gamma_{12}\frac{\partial P}{\partial t} + \omega^2\cdot P = -\frac{2\omega\,|\,d_{ab}\,|^2}{\hbar}\mu E\,, \tag{6}$$

$$\frac{\partial \mu}{\partial t} = \frac{2}{\hbar\omega} < E\frac{\partial P}{\partial t} >, \tag{7}$$

where the frequency ω of the transition between the levels corresponds to the frequency of the field, we neglect the relaxation of the inversion due to external causes, δ is the decrement of absorption of the field in the medium, d_{ab} is the matrix element of the dipole moment (more precisely, its projection onto the direction of the electric field), $\mu = n\cdot(\rho_a - \rho_b)$ the difference in populations per unit volume, ρ_a and ρ_b the relative populations of levels in absence of a field, γ_{12} is the width of the spectral line, n is the density of the dipoles of the active medium.

Here, the linewidth is inversely proportional to the lifetime of the states, which is due to relaxation processes. The fields are represented as $E = [E(t)\cdot\exp\{-i\omega t\} + E^*(t)\cdot\exp\{i\omega t\}]$ and $P = [P(t)\cdot\exp\{-i\omega t\} + P^*(t)\cdot\exp\{i\omega t\}]$. Wherein $< E^2 >= 2\,|\,E(t)\,|^2$. The number of field quanta is then equal $< E^2 > /4\pi\hbar\omega = 2\,|\,E\,|^2\;/4\pi\hbar\omega = N$. For slow varying amplitudes, the equations

$$\frac{\partial E}{\partial t} + \delta_D\cdot E = 2i\pi\omega P\,, \tag{8}$$

$$\frac{\partial P(t)}{\partial t} + \gamma_{12} P(t) = \frac{|d_{ab}|^2}{i\hbar} \mu E, \tag{9}$$

$$\frac{\partial \mu}{\partial t} = \frac{2i}{\hbar}[E(t)P^*(t) - E^*(t)P(t)], \tag{10}$$

here we additionally took into account the line width γ_{12}.
From equation (6), by simple transformations, we find

$$\frac{\partial N}{\partial t} + 2\delta N = \frac{i}{\hbar} \cdot [P(t)E^*(t) - P^*(t)E(t)], \tag{11}$$

where you can get the conservation law

$$\frac{\partial N}{\partial t} + 2\delta N + \frac{\partial \mu}{2\partial t} = 0. \tag{12}$$

DISSIPATIVE GENERATION MODE

We are interested in the case of a large level of radiation losses ($\Theta > 1$) in a resonator filled with an active substance. We believe that the emitters do not interact with each other, but exchange energy only with the integral field of the resonator. The increment of such dissipative instability is equal $\gamma = \tilde{\gamma}_0^2 / \delta_D >> \gamma_{12}$, that is, it significantly exceeds the natural line width, where the role of the nondissipative increment $\tilde{\gamma}_0 = \Omega_0 / \sqrt{2}$ is actually taken over by the Rabi frequency $\Omega_0 = 2\,|\,d_{ab}\,||\,E_\mu\,|/\hbar$, where $< E >_\mu{}^2 = 2\,|\,E_\mu\,|^2 = [4\pi\hbar\omega\mu_0]^{1/2}$. The equations that describe the radiation process of a quantum source (occupying a region b the size of the radiation wavelength) take the form

$$\frac{\partial \mathrm{M}}{\partial \tau} = -\mathrm{N}, \tag{13}$$

$$\frac{\partial \mathrm{N}}{\partial \tau} = \mathrm{M} \cdot \mathrm{N}, \tag{14}$$

where $\mathrm{M} = \mu / \mu_0$, $\mathrm{N} = 4(\delta_D^2 / \tilde{\gamma}_0^2) \cdot (N / \mu_0)$, $N =< E >^2 / 4\pi\hbar\omega$ - is the number of quanta, $\delta_D = (\int_S c < E >^2 / 4\pi) \cdot dS / \int_V (< E >^2 / 4\pi) \cdot dV \approx c / b$ is the effective decrement of the resonator field in the absence of an active medium, b is the size of the resonator. Along the length of the system b, as in [13,14], we arrange the sectors

$$\mathrm{N}_j(\tau = 0) = 2 \cdot \mathrm{N}(\tau = 0) \cdot \mathrm{Sin}^2\{2\pi \frac{j}{S} + \alpha\}, \tag{15}$$

moreover

$$\mathrm{N}(\tau) = \frac{1}{S} \sum_{j=1}^{S} \mathrm{N}_j(\tau) \tag{16}$$

Equations (13) - (14) for the sectors are:

$$\frac{\partial \mathrm{M}_j}{\partial \tau} = -\mathrm{N}_j, \tag{17}$$

$$\frac{\partial \mathrm{N}_j}{\partial \tau} = \mathrm{M}_j \cdot \mathrm{N}_j, \tag{18}$$

moreover

$$\mathrm{M}(\tau) = \frac{1}{S} \sum_{j=1}^{S} \mathrm{M}_j(\tau), \tag{19}$$

Parameters: $\mathrm{N}(\tau = 0) = 1/3600$, $\mathrm{M}(\tau = 0) = \mathrm{M}_j(\tau = 0) = 1$, $\mathrm{S} = 100$.
Figures 1 and 2 show the time dependence of the average number of quanta N and inversion M.

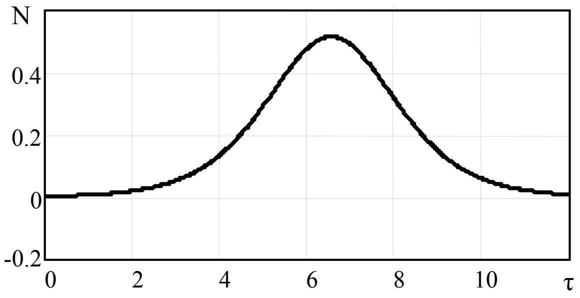


Figure 1. Time dependence of the average number of quanta N.

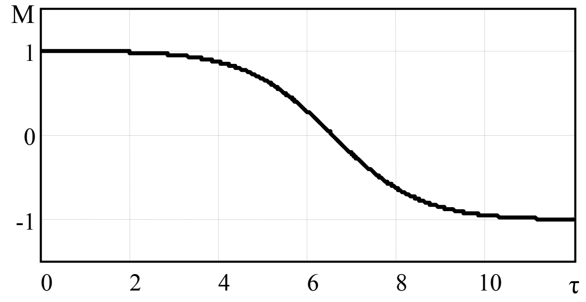


Figure 2. Time dependence of the mean inversion M.

Figure 3 shows the distribution of the inversion over the sectors Mj at different times: at the time of growth ($\tau = 4.5$), maximum ($\tau = 6.55$) and decrease ($\tau = 10$) of the number of quanta (see Fig. 1).

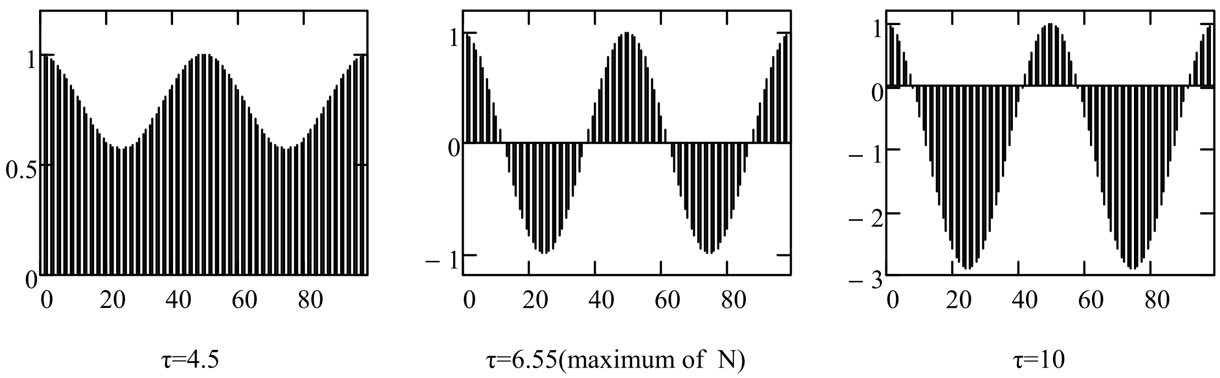


Figure 3. Distribution of inversion by sectors M_j at different points in time

SUPER RADIATION MODE

Previously, we considered the interaction of emitters with the field of a waveguide or resonator, and the emitters did not directly affect each other. In the same section, we will consider the interaction of emitters only with each other in the absence of an external resonator field. This interaction mode, with emerging self-synchronization of field generation sources, can be considered a superradiance mode. The equation for the field of an individual radiator is

$$\frac{\partial^2 E}{\partial t^2} - c^2 \frac{\partial^2 E}{\partial z^2} = 4\pi\omega^2 \cdot \overline{p} \cdot \mathrm{e}^{-i\omega t} \cdot \delta(z_0)\,, \tag{20}$$

where can we find the value

$$A(z,t) = \frac{i \cdot 2\pi \cdot \omega \cdot M}{c} \cdot \frac{1}{N} \sum_s \overline{p}(z_s,t) \cdot e^{ik|z-z_s|}\,, \tag{21}$$

where $M = n_0 \cdot b$ is the total number of emitters, and n_0 is the density of emitters per unit length.
From equations (1) - (3) we obtain a system of equations for the polarization and inversion of the j-th large particle-emitter.
where can we find the value

$$\frac{d}{dt}(\rho_{aa} - \rho_{bb}) = \frac{2i}{\hbar}[\overline{p}^* A - \overline{p} A^*]\,, \tag{22}$$

$$\frac{d}{dt}\overline{p} = -\frac{i}{\hbar}(\rho_{aa} - \rho_{bb}) \,|\, d_{ba} \,|^2\, A\,, \tag{23}$$

using the relations $\mathrm{P}_j = \mathrm{P}(z_j, \tau)$, $\mathrm{M}_j = \mathrm{M}(z_j, \tau)$, as well as $\mu_0 = \mu_j(\tau = 0)$,

$z=\frac{2\pi}{k}Z,\ \ \mu=\mu_0\cdot\mathrm{M},\ \ \bar{p}=|d_{ab}|\cdot\mu_0\cdot\mathrm{P},\ \ t=\tau/\gamma,\ \ \Gamma_{12}=\frac{\gamma_{12}}{\gamma},\ \ n_0\cdot b=M$, , where $\gamma=\frac{2\pi\cdot\omega\cdot|d_{ba}|^2\cdot\mu_0\cdot n_0\cdot b}{\hbar c}$ is the increment of the process, we write system (20) - (21) in the form

$$\frac{d}{dt}\mathrm{M}_j=-2\cdot[P_j*\mathrm{A}_j+P_j\mathrm{A}_j*], \tag{24}$$

$$\frac{d}{dt}P_j=\mathrm{M}_j\cdot\mathrm{A}_j, \tag{25}$$

where for $\mathrm{A}_j=\mathrm{A}(Z_j,\tau)$ the relation

$$\mathrm{A}(Z,\tau)=\frac{1}{N}\sum_s \mathrm{P}(Z_s,\tau)\cdot e^{i2\pi|Z-Z_s|}. \tag{26}$$

The last expression can be represented as $\mathrm{A}(Z,\tau)=|\mathrm{A}(Z,\tau)|\cdot e^{i\varphi(Z,\tau)}$, $\varphi(Z,\tau)$ is the phase of the field at point Z. It should be borne in mind that for the dimensionless representation of the field we have divided by $\gamma\hbar/|d_{ba}|$. Then, for the total amplitude of the electric field in this normalization, the expression $\mathrm{E}=2|\mathrm{A}(Z,\tau)|$ is valid.

It is important to note that the growth rate $\gamma=2\pi\cdot\omega\cdot|d_{ba}|^2\cdot\mu_{01}\cdot n_0\cdot b/\hbar c$ in the semiclassical model of superradiance corresponds to the growth rate $\gamma=\tilde{\gamma}_0^2/\delta_D$ of dissipative instability.

For 4000 emitters distributed at the wavelength, at $\mathrm{P}_j(\tau=0)=\mathrm{P}_0\exp(i\psi_j)$, where the polarization phases ψ_j of the emitters are random values $\psi_j\subset(0\div 2\pi)$, $\mathrm{P}_0=0.1$, $\mathrm{M}(\tau=0)=1$, $\Gamma_{12}=0$,we obtain the following results of the numerical solution. Figure 4 shows the time dependences of the field amplitude on the left and right of the system and the maximum inside the emitter and the average inversion of the system. Figure 5 shows the time dependence of the mean inversion of the system.

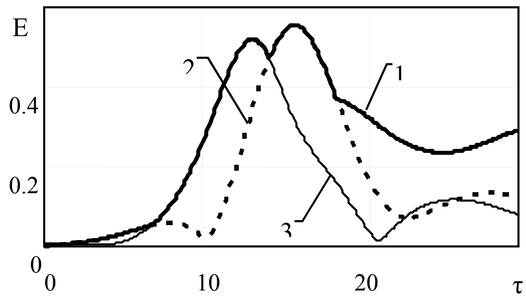


Figure 4. Dependence of the field amplitude on time, $1-\max_Z(\mathrm{E}(Z,\tau)),\ 2-\mathrm{E}(Z=0,\tau),\ 3-\mathrm{E}(Z=1,\tau)$.

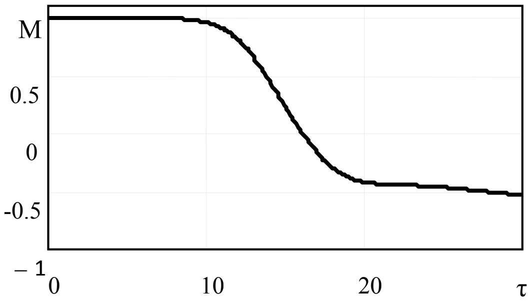


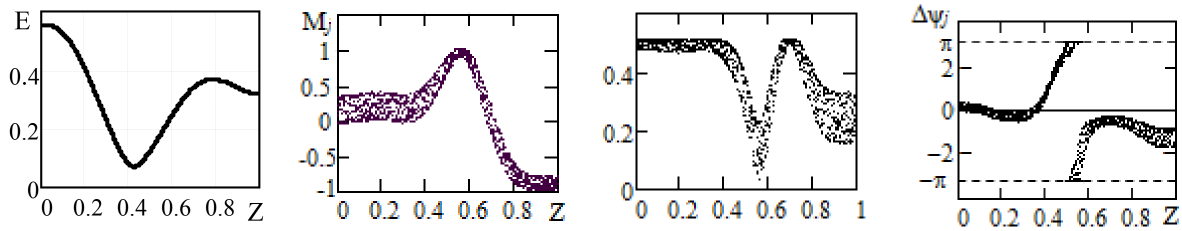
Figure 5. Dependence of the average inversion of the system $\mathrm{M}=\frac{1}{N}\sum_j \mathrm{M}(Z_j,\tau)$ on time

As can be seen from Figures 4 and 5, energy is pumped from the system of emitters into the electromagnetic field. The field has two approximately equal maxima at times τ = 13.2 (E = 0.52) and τ = 15.8 (E = 0.555). The first maximum is on the right edge of the system (Z = 1), the second is on the left (Z = 0). When setting other random initial phases of the polarization of the emitters, the field maximum of approximately the same magnitude and at approximately the same time was observed only at one of the edges of the system.

From the initial moment to reaching the maximum, the formation of a field with a minimum in the middle of the system is observed. In this case, there also occurs (mainly in the region of high fields) a decrease in the inversion and an increase in the polarization modulus. The polarization phases are also synchronized. The polarizations of neighboring emitters are rather quickly collected in a narrow band of angles. In the region of maximum fields, the polarization phases of the emitters are also synchronized with the field phase. This leads to the fact that the difference between the phase of the polarization of the emitter at a point and the phase of the field at this point is close to zero. Figure 6 shows the distributions of some characteristics at the moment τ = 15.8 (the second maximum of the field on the left edge)

Figure 6a) demonstrates a field dip in the middle of the system. In fig. 6b) shows the greatest decrease in inversion at the right edge, where the first field maximum was formed; the decrease at the left edge occurs more slowly in accordance with the slower formation of the field maximum in this region.

In the region of the field maximum, the polarization modulus is larger (Fig. 6c) and the greatest synchronization of the polarization phase and the field phase (Fig. 6d). Note that at the instant τ = 13.2, in the region of the field maximum on the right edge, there was the greatest synchronization of the polarization phase and the field phase, and the inversion decreased.



a) b) c) d)

Figure 6. Distribution along the length of the system of quantities
a) field modulus, b) emitter inversion, c) emitter polarization module, d) difference between the polarization phase of the emitter and the field phase.

Further, the field falls rapidly along the edges of the system (faster on the right edge) and an area of relatively larger field in the center is formed, although it does not reach its maximum values. Figure 7-8 shows the field and inversion distribution at τ = 30.

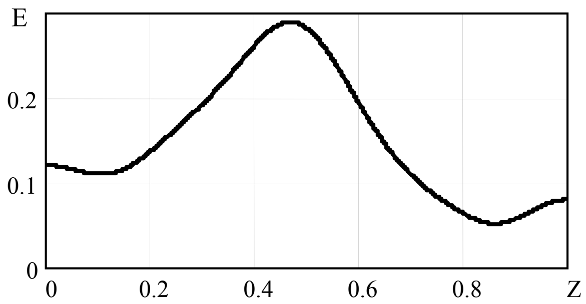


Figure 7. Distribution of the field modulus along the length of the system at τ = 30.

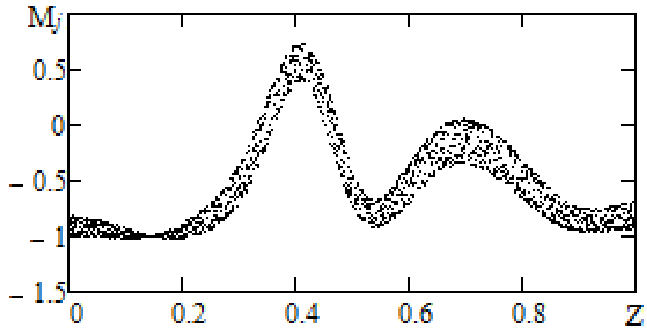


Figure 8. Distribution of the inversion of emitters along the length of the system at τ = 30.

CONCLUSIONS

The similarity of dissipative generation regimes and superradiance regimes for systems of excited quantum emitters placed in an open cavity is shown.

In open systems, with a sufficiently high level of radiation from the ends of the system, both a dissipative excitation mode of a waveguide or resonator field by non-interacting with each other emitters, and a superradiance mode of the system, when there is no waveguide field, and each emitter participates in creating a sufficiently intense integral field, are possible.

The dissipative generation mode is realized in the case of the existence of only a resonator field due to reflections from the ends of the system. For this generation mode, the decrement of oscillations in the waveguide in the absence of emitters turns out to be greater than the increment of the resulting instability of the system of emitters placed in the resonator. The influence of the emitters on each other and the sum of their own fields are neglected. To describe the process, the equations of the semiclassical theory based on the use of the density matrix are quite sufficient.

The superradiance mode can manifest itself in the case when there is no resonator or waveguide field. Then taking into account the eigenfields of the oscillators becomes essential. To simulate the superradiance process, we use large emitting particles, which can be described by equations for the density matrix. It is believed that the interaction of quantum emitters in this case is due to electromagnetic fields under conditions when the overlap of their wave functions is insignificant. When the emitters interact, an integral field is formed in the resonator, an increase in the intensity of which leads to synchronization of the emitters into the cavity volume.

It is shown that the characteristic times of the development of the process, as well as the attainable amplitudes of the excited fields for dissipative regimes of generation and regimes of superradiance of emitters filling an open cavity, are practically the same. The asymmetric behavior of the field in the superradiance regime is associated with the choice of the initial conditions. You can make sure that the field strength in the superradiance mode is expressed in terms of the radiation intensity, that is, where, (see the notation in front of formula (13)).

Two values of the maxima in Fig. 4 correspond to values equal to 0.27 and 0.31, respectively. Thus, for the same resonator, the increments of superradiance and dissipative instability are practically of the same order of magnitude, and the intensities of the excited field turn out to be comparable. The saturation mechanism of instability regime is the decrease of the inversion level and also the appearance of resonator regions where induced attenuation dominates [13,14].

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НАПІВКЛАЧИСНІ МОДЕЛІ ДИСИПАТИВНОГО РЕЖИМУ НЕСТІЙКОСТІ ТА НАДВИПРОМІНЮВАННЯ СИСТЕМИ КВАНТОВИХ ВИПРОМІНЮВАЧІВ

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У роботі обговорюється подібність дисипативних режимів генерації та режимів надвипромінювання для систем збуджених квантових випромінювачів, поміщених у відкритий резонатор. У разі існування резонаторного поля за рахунок відбиття від торців системи звичайно реалізується дисипативний режим генерації. При цьому декремент коливань у хвилеводі при відсутності випромінювачів виявляється більше інкремента виникаючої нестійкості системи випромінювачів, поміщеної в резонатор. При описі цього режиму вплив випромінювачів один на одного і сума їх власних полів нехтується. Поле резонатора змушує осцилятори випромінювати або поглинати кванти синхронно з ним, в залежності від локального значення інверсії заселеності. Генерація набуває слабо осциляторний характер через несинхронну зміну інверсії заселеності системи випромінюючих диполів (нутації), що мають основний і збуджений рівні енергії. Для опису процесу цілком достатньо рівнянь напівкласичної теорії, заснованої на використанні матриці щільності. У разі, коли резонаторне або хвилевідне поле відсутнє, врахування власних полів осциляторів стає істотним. Для моделювання процесу надвипромінювання застосовуються великі частки-випромінювачі, для опису яких слід скористатися рівняннями для матриці щільності. Показано, що взаємодія квантових випромінювачів в цьому випадку обумовлена електромагнітними полями в умовах, коли перекриття їх хвильових функцій несуттєво. Отримані рівняння, що дозволяють розглянути процес взаємодії випромінювачів. При взаємодії випромінювачів в резонаторі формується інтегральне поле, зростання інтенсивності якого призводить до синхронізації випромінювачів. Показано що характерні часи розвитку процесу, а також досяжні амплітуди збуджених полів для дисипативних режимів генерації та режимів надвипромінювання випромінювачів, що заповнюють відкритий резонатор, виявляються порівнюваними.
КЛЮЧОВІ СЛОВА: дисипативні режими генерації, надвипромінювання, відкритий резонатор