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ON THE DEVELOPMENT OF SUPER-RADIATION IN NOISE CONDITION

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The influence of noise on field generation in the superradiant regime, when all oscillators interact with each other, is discussed. The process of phase synchronization of excited oscillators is considered and it is noted that its efficiency is affected by the spread of their amplitudes. External noise leads to phase mismatch and can suppress generation. The behavior of a system of oscillators near the generation threshold is considered. It has been shown that even below the threshold, a small external field can provoke generation up to amplitudes characteristic of processes in the absence of noise.

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INTRODUCTION

The superradiance field arises as the total field of initially spontaneously emitting emitters and oscillators, even in the absence of a waveguide and resonator. The total field of a system of unsynchronized emitters or oscillators at the initial moment is spontaneous. Nevertheless, in a system of oscillators, it is possible for their phases to synchronize with the phases of external fields that arise sporadically in the system or are imposed by external radiation of small amplitude. It is this phenomenon that determines the increase in the coherence of the resulting stimulated radiation. This process is commonly called superradiation. Previously, this phenomenon was called collective spontaneous radiation, which can cause misunderstandings, although V.L. Ginzburg definitely attributed superradiation to induced effects [1]. Therefore, the most important thing for the implementation of superradiation generators is to study the nature of generation of this type, and especially the influence of noise, which can destroy the synchronization process of the emitters. These are the questions that are addressed in this work.

1. EQUATIONS OF THE OSCILLATOR SYSTEM MODEL

Let us discuss the physical model of the generation of electromagnetic oscillations in a system of stationary oscillators [2] in conditions of the development of the superradiance process and taking into account external noise. Let's consider an oscillator whose charge (electron) moves along the OX axis, that is $x(t) = i \cdot a \cdot \exp\{-i\omega t + i\psi\}$, $\mathrm{Re}\, x = a \cdot \sin(\omega t - \psi)$, where $\vec{r} = (x(t), 0, z_0)$. The speed and current can be written as $dx/dt = a \cdot \omega \cdot \exp\{-i\omega t + i\psi\}$ and $J_x = -e \cdot dx/dt = -e \cdot a \cdot \omega \cdot \exp\{-i\omega t + i\psi\}$, $a_0 = a(t=0))$ – the initial amplitude of each of the oscillators of the system.

In the absence of a resonator or waveguide field, the equation describing the change in the complex amplitude of an individual oscillator takes the form [3, 4]

$$\frac{d\,\mathrm{A}_j}{d\tau} = \frac{i\alpha}{2} \cdot \left|\mathrm{A}_j\right|^2 \mathrm{A}_j - \mathrm{E}(Z_j, \tau) + i \cdot \delta \cdot r_j(\tau) \cdot \mathrm{A}_j, \qquad (1)$$

where in this work we additionally introduced the last term on the right side of (1), which takes into account the influence of external noise. Here $r_j(\tau)$ – takes random values from -1 to +1, changing at intervals $\Delta\tau$ on a selected time scale, δ – is the maximum value of this impact. The electric field of radiation from a system of oscillators [3, 4]

$$\mathrm{E}(Z, \tau) = \mathrm{E}_{sr} = \frac{1}{N\theta} \sum_{s=1}^{N} \mathrm{A}_s(\tau)\, e^{i 2\pi |Z - Z_s|}. \qquad (2)$$

The following notations are used here: $\frac{e\,|E(t)|\exp\{i\varphi\}}{m\gamma_0\omega_0 a_0} = \mathrm{E}(t)$; $\gamma_0 t = \tau$; E, φ – amplitude and phase; c – group velocity of oscillations, the time scale is determined by the relation $\gamma_0^2 = \pi e^2 n_0 / m = \omega_{pe}^2 / 4$; $\mathrm{A}_j = a_j / a_0$ – relative complex amplitude of the oscillator; $kz_j = 2\pi Z_j$; $\theta = c/\gamma_0 b = \delta/\gamma_0$; b – longitudinal size of the system of oscillators, the density of which n_0; $\alpha = \frac{3\omega}{4\gamma_0}(k_0 a_0)^2$ – takes into account the weak dependence of the relativistic mass of the particle on the speed, charge and mass of which e, m. It is easy to see that c/b proportional to the ratio of the energy flow from the end of the system to the total energy in its volume, which corresponds to the radiative damping of oscillations, has the meaning of the plasma frequency ω_{pe} in the system. Note that the same system of equations (1), (2) can be obtained by simplifying the systems of equations for TE and TM cyclotron waves excited by rotating electrons in the presence of a constant magnetic field [3, 4] subject to the following conditions: $n = 1$, $\Delta = 0$, $\varphi \to -\varphi$, $\psi \leftrightarrow 2\pi\zeta + \pi/2$, $R \to 0$ for small a_i.

2. GENERATION CONDITIONS

Nonlinearity of oscillators. It turns out that a decrease in the degree of nonlinearity of the oscillators leads to a decrease in the maximum amplitude of the superradiation field and a decrease in the level of coherence of radiation even in the absence of noise.

$\delta = 0$. When $\alpha = 0$ superradiation field are not excited [5, 6]. With weak relativism, for generation to occur, it is necessary to use an external initiating field.

Phase synchronization. The field in the system increases due to the synchronization of the phases of pre-excited oscillators in its volume with the phase of the integral field (see, for example, [7]). This field can be either the field of a fluctuation (if $\alpha \propto 1$) or an external initiating field. The equation for the oscillator phase, which follows from (2), takes the form

$$\frac{d\psi_j}{dt} - \frac{\alpha}{2}\left|\mathrm{A}_j\right|^2 - \delta r_j = -\left\{\frac{|\,\mathrm{E}(Z_j,\tau)\,|}{|\,\mathrm{A}_j\,|}\right\}\sin(\varphi - \psi_j)\,. \quad (3)$$

You can pay attention to the fact that the right side of the last equation is quite large $|\,\mathrm{E}(Z_j,\tau)/\mathrm{A}_j\,| >> 1$. This condition, with weak noise, can force the phase of an individual oscillator to synchronize with the phase of the total field of the ensemble $\psi_j \to \varphi$. However, it turns out that effective synchronization of oscillator phases is possible only with a small spread of oscillator amplitudes $|\,\mathrm{E}(Z_j,\tau)/\mathrm{A}_j\,| \approx Const$, which was previously observed in previous works [7]. If the spread of oscillator amplitudes is significant, it is not possible to ensure their synchronization with the external field.

Even in the absence of noise ($\delta = 0$) for excited $\mathrm{A}_i = 1;\,(i = 1,...N)$ nonlinear ($\alpha \propto 1$) oscillators, spontaneous fields arising in the system can lead to an increase in the superradiance field, which is an induced field (see, for example, [1]). When noise appears in the system, which is modeled by the last term on the right side of (2), the field growth can be suppressed. The average intensity of the resulting turbulence fields will not exceed the spontaneous level.

3. GENERATION OF SUPER-RADIATION IN NOISE CONDITIONS

Random exposure (noise simulator), switched at intervals $\Delta\tau = 0.4$, leads to weakening of synchronization or even complete chaotization of phases. The calculation results below use the following parameters: number of particles $N = 900$, nonlinearity parameter $\alpha = 1$, noise switching interval $\Delta\tau = 0.4$, system length $b = 1$ (one wavelength).

Fig. 1a shows the change in the average value of the squared amplitude in the system $A_{av}^2 = \frac{1}{N}\sum_{s=1}^{N}\left|\mathrm{A}_s\right|^2$ over time for different values of the external noise level.

In Fig. 1b shows the behavior of the maximum field amplitude and the volume-averaged field amplitude in a system of oscillators in the absence of noise ($\delta = 0$).

Even from these figures one can see the existence of a threshold. If $\delta = 0...1$, the field value reaches 0.22 at the selected scale. Below the threshold value $\delta_{thr} \propto 1.5$ there is no field growth, the energy extraction from the oscillators is weakened (the average energy remains at the level of 96% of the initial one).

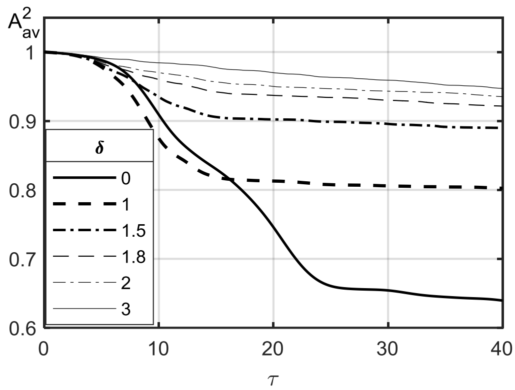

Fig. 1a. Time dependence of the average value of the squared amplitude for different levels of external noise

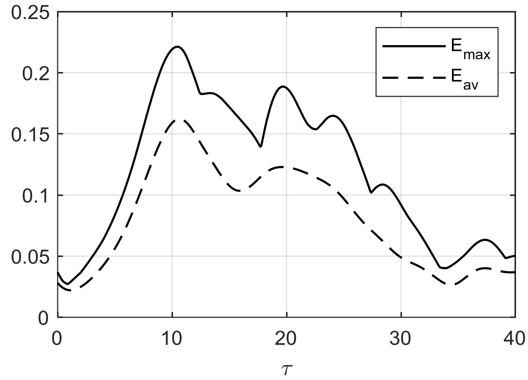

Fig. 1b. Time dependence of the maximum and average field in the system in the absence of external noise

In this case, a turbulent state is formed with an average field value E_{av} close to the spontaneous electric field strength level of 0.03…0.04. The peak level of fluctuations $E_{\max}$ exceeds the average level by two or more times (Fig. 2).

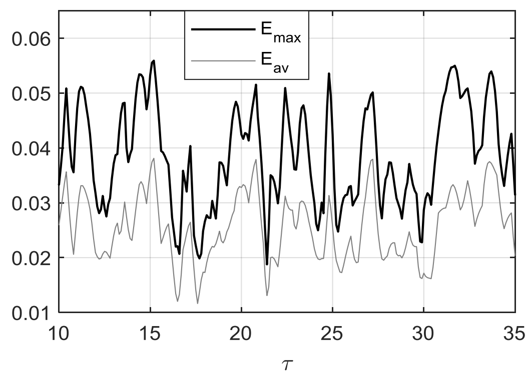

Fig. 2. Average field values E_{av} and peak values $E_{\max}$ of fluctuations at noise level $\delta = 3$

When approaching the threshold, the average values of the amplitudes of the oscillators (at $\delta \propto 1.8$, $A_{av}^2 < 0.97$) change slightly, that is, no noticeable energy extraction from the system of oscillators is observed however, when approaching the threshold, the peak values of fluctuations increase (Fig. 3).

By considering the region near and below the threshold, it is possible to find out how the external field influences the occurrence and development of generation under superradiance conditions. The time dependence of the maximum generation field of the oscillator system at different amplitudes of the external field is shown in Fig. 4.

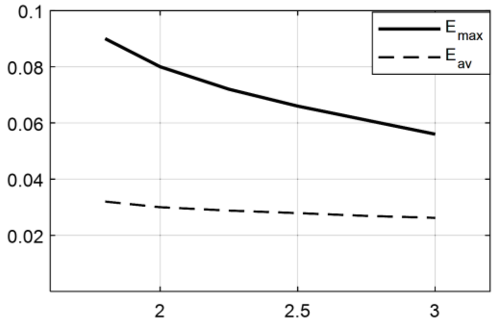

Fig. 3. Growth of oscillations when approaching the generation development threshold

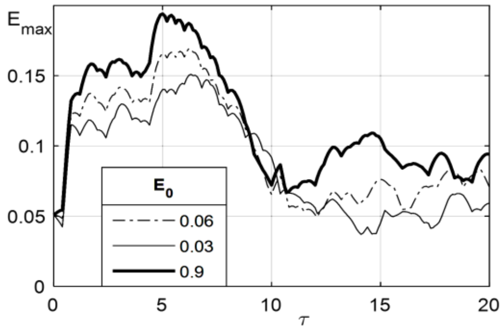

Fig. 4. Influence of an external initiating field E_0 = 0.03; 0.06; 0.09 on generation under superradiance conditions

In Fig. 4 it can be seen that even in the case of noise ($\delta \approx 1.8$), an increase in the amplitude of the external initiating field leads to an increase in the maximum generation field up to values that are realized in the absence of noise.

CONCLUSIONS

A system of excited oscillators is capable of generating an electromagnetic field in superradiance mode. This mode is implemented in conditions where all oscillators interact with each other. In this case, there is no field of the waveguide or resonator. It is important to note that the oscillators must be nonlinear, and the stronger the nonlinearity, the greater the field maximum values can be counted on. It is shown that noise in the system forms the lasing threshold. When this threshold is exceeded, even in the absence of an initiating external field, a significant part of the excited oscillators are capable of generating fields whose maximum amplitudes are comparable to the generation amplitudes in the absence of noise. Below the presented threshold, no field growth is observed. The main role in the development of lasing in the superradiation regime is played by synchronization of the phases of the oscillators with the phase of the field external to the oscillator. This field can form inside the system, in the absence or at a low noise level. At a noise level when the system is below the generation threshold, it is the external initiating field that can provoke fairly effective field generation, comparable to the levels achieved in the absence of noise. It should be noted, however, that an increase in the amplitude spread of excited oscillators can suppress generation both in the absence of noise and in the presence of an external initiating field.

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ПРО РОЗВИТОК НАДВИПРОМІНЮВАННЯ В УМОВАХ ШУМУ

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Обговорюється вплив шуму на генерацію поля у режимі надвипромінювання, коли всі осцилятори взаємодіють один з одним. Розглянуто процес синхронізації фаз збуджених осциляторів і зазначено, що його ефективність впливає на розкид їх амплітуд. Зовнішній шум призводить до неузгодженості фаз і здатний придушити генерацію. Розглядається поведінка системи осциляторів поблизу представленого у роботі порога. Показано, що навіть нижче за поріг генерації невеликим зовнішнім полем можна спровокувати генерацію, причому до амплітуд, характерних при відсутності шуму.