SLOWING-DOWN OF TRANSIENT PROCESSES UPON THE FORMATION OF THE POWER-SPECTRUM FINE STRUCTURE OF A MICROWAVE PHONON LASER (PHASER)

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The processes of regular and chaotic formations of a fine structure (FS) in the power spectrum of an autonomous phonon laser (phaser) have been investigated. The pronounced slowing-down of transient processes in the course of the FS formation has been observed experimentally, provided the detuning in the magnetic field and the pump frequency. An explanation of the slowing-down observed has been proposed in the framework of the self-organized bottleneck model, which had been developed earlier for distributed excitable systems to emulate the dynamics of lasers of class B.

1. Introduction

The problem of studying the nonlinear processes occurring in open dissipative systems which possess a complex phase-space structure is challenging for a number of branches of modern physics [1]. In particular, the laser-based and other nonlinear optical systems are studied intensively in this field of science nowadays [2, 3], and a number of important fundamental and applied results has already been obtained. Lately, the ideas of quantum electronics have also deeply penetrated into adjacent branches of modern physics. In particular, new nonlinear phenomena, which arise under the quantum-mechanical amplification or generation of tera-, hyper-, or ultrasonic oscillations in nonequilibrium (inverse) acoustic and nanomechanical dissipative systems of various origins, have been predicted theoretically and discovered experimentally [4–6]. The researches concerning the conditions, under which the formation of inversive states and the purposeful control over nonlinear processes in such systems (the acoustic analogs of lasers) become possible, are of significant independent interest.

As has already been emphasized in work [5], if one confines the consideration to the quantum-mechanical amplification and generation of *hypersound*, i.e. the acoustic waves within the micrometer range, the following circumstances invoke the greatest interest. A microwave phonon laser (phaser) emits radiation with a wavelength of 1–3 μm, which corresponds to the wavelength of electromagnetic radiation in the near infrared range, where many ordinary lasers generate as well. At the same time, the hypersonic speed in the active phaser medium is 5 orders of magnitude slower than the speed of electromagnetic waves. Accordingly, the frequency of the stimulated emission (SE) in a phaser amounts to $\omega = 3 \div 10$ GHz only, which is about the same 5 orders of magnitude lower than the frequency of the optical (electromagnetic) lasing. Therefore, the relative intensity of the spontaneous component J_{spont} of emission in a phaser is 15 orders of magnitude lower than that in an ordinary optical laser (because $J_{\text{spont}} \propto \omega^3$), whereas the lengths of corresponding acoustic and electromagnetic waves coincide.

The low level of the quantum noise in phasers opens new opportunities for studying the nonlinear phenomena in nonequilibrium systems. This conclusion has already been confirmed experimentally for a phaser with an active ruby crystal (Cr^{3+}:Al_2O_3). In works [5, 7], a new nonlinear resonance (λ-resonance), which is accompanied by a number of interesting dynamic phenomena, has been discovered experimentally and studied in a non-autonomous ruby laser. This resonance arises at a pumping or a magnetic-field modulation in the range of ultralow frequencies $\omega_m \approx \omega_\lambda$, where $\omega_\lambda/2\pi \approx 10$ Hz [5]. It is considerably lower that the typical frequencies of the phaser relaxation resonance $\omega_\nu/2\pi \approx 70 \div 300$ Hz, which was observed earlier in works [8–10] and is an analog of the laser relaxation resonance.

In works [5,7], it has been discovered experimentally that a plenty of coexisting states of the spin-phonon system emerges in the range of the λ-resonance and the very slow regular transitions, which remind autowave motions, occur between them. The period of the full cycle of such transitions reaches huge values and exceeds $10^3 - 10^4$ s at $\omega_m \approx \omega_\lambda$ [5]. This is several orders of magnitude longer than the period $\tau_m \equiv 2\pi/\omega_m$ of an external force that modulates the phaser pumping system.

It should be mentioned that the slowing-down of transient processes in paramagnetic crystals, which accompanies the saturation of spin transitions, has already been studied earlier [11] in the case of the so-called phonon bottleneck (PB) effect induced by non-coherent (thermal) effects in a resonant spin-phonon system which interacts with a thermostat. However, in the 1970s, it has been proved experimentally [12—14] that, at least in the micrometer range, the quantum amplification and stationary autogeneration of phonons arise owing just in the absence of the PB effect, which could only interfere with the normal functioning of a phaser in this case. Anyway, the PB effect in the micrometer range of frequencies and at temperatures of liquid helium has been revealed neither in our researches, nor in the works of other authors dealing with a pink ruby medium and known to us. In particular, our experimental data [13, 14] have demonstrated that the maximal lifetime of resonant phonons with a frequency of about 10 GHz is many orders of magnitude shorter at temperatures $\theta = 1.7 \div 4.2$ K than the time of the longitudinal spin relaxation $\tau_1 \approx 0.1 \div 1$ s in a pink ruby at the same frequency.

Thus, the emergence of slow processes, which were observed in a non-autonomous phaser [5, 7], cannot evidently be a result of the noncoherent PB influence. The slowing-down of the spin-phonon energy exchange reflects, as was shown in work [5], the peculiarities of the self-organization of dissipative structures in the spin-phonon system of such a phaser, provided a strong external perturbation of the inverse state of paramagnetic centers. Does such or similar slowing-down of spin-phonon processes exist in an *autonomous* phaser, where the self-organization in the spin-phonon system is not excited by an external force at all? The main aim of this work was the search for the answer to this question. The results of theoretical researches [15, 16], which have been published recently, served as an additional motivation for this work to be fulfilled. These works, in particular, have demonstrated that the formation and development of coherent dissipative structures can slow down the transient processes in autonomous active systems substantially.

2. Phaser System

The experimental part of the work was carried out making use of a phaser, the main element of which was a ruby acoustic Fabry—Perot resonator (AFPR) described in works [5, 7]. As was already indicated in work [7], a ruby phaser is an acoustic analog of the class-B lasers [17], where the slow population inversion of the energy levels of active centers is determinative, while the system of field excitations "adjusts itself" to its running. The population inversion of the active phaser centers which include paramagnetic Cr^{3+} ions is formed by the microwave pump field generated with the help of an electromagnetic bulk pump resonator (EBPR) with the AFPR inside.

On one of the acoustic mirrors, there was mounted a piezoelectric transducer composed of a thin ZnO film and an Al interlayer. This transducer was able to register the acoustic SE that arose in the AFPR in the vicinity of its eigenfrequencies $\omega_n/2\pi \approx 9$ GHz $(\Delta_n/2\pi \equiv (\omega_n - \omega_{n-1})/2\pi = 310$ kHz), when the corresponding spin transitions of Cr^{3+} ions were being pumped. The transducer was two-target; this means that, making use of a microwave external generator that excites hypersonic vibrations in the ZnO film, one can inject the ordinary hypersound, which is not connected with the PB effect, with the frequency $\omega_{\rm inj}$ into the AFPR.

Other details concerning the piezoelectric transducer, the AFPR, the EBPR, and the control parameters (the static magnetic field $\vec{H}$, the pump frequency $\omega_{\rm pump}$, the pump power P, etc.) can be found in work [5]. However, in contrast to work [5], the measurements of SE were carried out provided that any modulation of the control parameters was absent. Therefore, all the SE modes that were observed in this work concern exclusively the autonomous phaser.

3. Absorption, Amplification, and Autogeneration of Hypersound in the Phaser System

3.1. Absorption of hypersound in the absence of pumping

Provided that the pumping is absent ($P = 0$) and the amplitude and direction of $\vec{H}$ are far from the lines of the acoustic paramagnetic resonance (APR) of the system Al_2O_3:Cr^{3+}, the absorption of hypersound with the frequency $\omega_{\rm inj}$, which has been injected into the AFPR, is governed by two following factors:

(a) the coefficient of non-resonant volume attenuation of hypersound $\eta_{\rm vol}$, which also includes losses at the lateral surfaces of the AFPR; and

(b) the coefficient of hypersound losses at the AFPR mirrors, $\eta_{\rm mirr}$, which takes into account the additional acoustic loading at the mirror, where a piezoelectric transducer is located.

If $\omega_{\rm inj} \approx \omega_n$, acoustic microwave resonances similar to ordinary electromagnetic ones in an optical Fabry—Perot resonator are observed in the AFPR.

Provided $P = 0$ and $\omega_{\rm inj} = {\rm const}$, the amplitude and direction of $\vec{H}$ can be tuned in such a manner that the APR arises, namely, $\vec{H} \approx \vec{H}_{0,S}$, where $\vec{H}_{0,S}$ is the magnetic-field coordinate of the APR line vertex. In other words, the split frequency for a certain pair of energy levels $\mathcal{E}_m$ and $\mathcal{E}_n$ in the Al_2O_3:Cr^{3+} system should approximately coincide with $\omega_{\rm inj}$. The quantum-mechanical transition $\mathcal{E}_m \leftrightarrow \mathcal{E}_n$ has to be allowed in order that the system can interact with hypersound of the selected type. In this case, the mechanisms of absorption that were indicated above are joined by another one – the resonant paramagnetic absorption of hypersound – which depends strongly both on $\omega_{\rm inj}$ and $\vec{H}$, as well as on the hypersound type (longitudinal, fast transverse, slow transverse) [11].

3.2. Phaser amplification and hypersound autogeneration conditions

If the pumping is switched on ($P > 0$), the line vertex of the electron spin resonance (ESR) $\vec{H}_{0,P}$ at a pump frequency does not coincide with that of the APR line $\vec{H}_{0,S}$ at the frequency $\omega_{\rm inj}$. But if the condition $\vec{H}_{0,P} = \vec{H}_{0,S} \equiv \vec{H}_0$ is satisfied, the value of P is sufficient to saturate the ESR line, and the relation between $\omega_{\rm pump}$ and $\omega_{\rm inj}$ corresponds to the conditions of the inversion of populations of the levels $\mathcal{E}_m$ and $\mathcal{E}_n$, the paramagnetic absorption of injected hypersound is substituted by its phaser amplification (as for the specific conditions for the inversion of the APR line at the ESR saturation, see work [5]).

If the non-resonant losses of hypersound ($\eta_{\rm vol}$ and $\eta_{\rm mirr}$) are totally compensated owing to the phaser amplification, the phaser generation self-excitation arises. In this work, the geometrical axis of the AFPR $\vec{\mathcal{O}}_C$ coincides with the ruby's crystallographic axis of the third order $\vec{\mathcal{O}}_3$. It is known that, in the case of transverse hypersound with the wave vector $\vec{k}_T \| \vec{\mathcal{O}}_3$, the so-called conical refraction takes place [18]. This phenomenon is connected with the degeneration of the transverse mode. Hence, only longitudinal hypersound modes with the wave vector $\vec{k}_L \| \vec{\mathcal{O}}_C \| \vec{\mathcal{O}}_3$ possess a high Q-factor in such an AFPR.

Thus, the considered compensation of non-resonant hypersound losses arises, first of all, at the longitudinal AFPR mode ω_1, which is located most closely to the center of the inverted APR line. For this mode, the condition

$$Q^{(1)}_{\rm eff}(P, \vec{H}, \omega_1) < 0 \qquad (1)$$

holds true ahead of all other modes, as P increases. Here, $Q^{(1)}_{\rm eff}$ is the effective acoustic Q-factor of the phaser system for the mode ω_1 under pumping, which is determined by the relations

$$\frac{1}{Q^{(1)}_{\rm eff}} = \frac{1}{Q^{(1)}_{\rm vol}} + \frac{1}{Q^{(1)}_{\rm mirr}} + \frac{1}{Q^{(1)}_{\rm magn}} = \frac{1}{Q^{(1)}_{C}} + \frac{1}{Q^{(1)}_{\rm magn}}, \qquad (2)$$

where $Q^{(1)}_{\rm vol} = k_L/\eta_{\rm vol}$, $Q^{(1)}_{\rm mirr} = k_L/\eta_{\rm mirr}$, $k_L = \left|\vec{k}_L\right| = \omega_1/V_L$, V_L is the phase velocity of hypersound, $Q^{(1)}_C$ the intrinsic Q-factor of the AFPR at the ω_1 mode in the absence of pumping, and $Q^{(1)}_{\rm magn}$ the magnetic Q-factor of this mode under pumping.

In contrast to $Q^{(1)}_C$, the magnetic Q-factor $Q^{(1)}_{\rm magn}$ can be negative. It looks like

$$Q^{(1)}_{\rm magn} = -k_L/\alpha_1(P, \vec{H}, \omega_1) \equiv$$

$$\equiv -k_L \left[K(P, \vec{H})\sigma(\vec{H}, \omega_1)\right]^{-1}, \qquad (3)$$

where α_1 is the coefficient of quantum amplification of hypersound for the mode under consideration, K the inversion ratio for the APR line (in the case of inversion, $K > 0$), and σ the coefficient of paramagnetic absorption of hypersound at $P = 0$.

Following work [11], we write down the expression for σ at the spin transition $\mathcal{E}_m \leftrightarrow \mathcal{E}_n$ in the form

$$\sigma_{mn} = \frac{2\pi^2 C_a \nu^2 g(\nu) |\Phi_{mn}|^2}{(2S+1)\rho' V_L^3 k_B T}, \qquad (4)$$

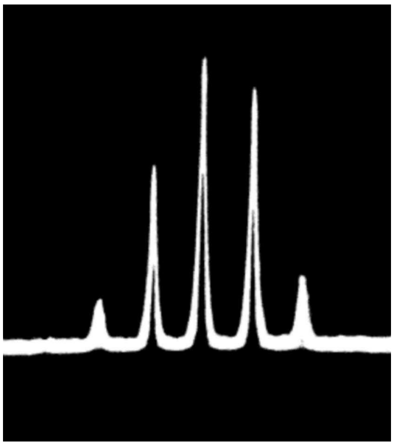

Fig. 1. Power spectrum of microwave phonon SE at $\Delta_P = \Delta_H = 0$. The frequency interval between the sequential CS modes of phonon emission amounts to 310 kHz. The cryostat temperature $\theta = 1.7$ K

where C_a is the concentration of paramagnetic centers, $\nu = \omega/2\pi$, $g(\nu)$ is the form-factor of the APR line, ρ' the crystal density, k_B the Boltzmann constant, Φ_{mn} the coupling parameter of the spin transition $\mathcal{E}_m \leftrightarrow \mathcal{E}_n$ with hypersound.

The matrix element Φ_{mn} for a longitudinal hypersonic wave that propagates along the ruby's axis of the third order $\vec{\mathcal{O}}_3$ is determined as follows (the coordinate axis z is parallel to $\vec{\mathcal{O}}_3$):

$$\Phi_{mn} = \frac{\partial}{\partial \varepsilon_{zz}} \langle \psi_m | \hat{\mathcal{H}} | \psi_n \rangle =$$

$$= \frac{G_{33}}{2} \big(3 \langle \psi_m | \hat{S}_z^2 | \psi_n \rangle - S(S+1) \langle \psi_m | \psi_n \rangle \big). \quad (5)$$

Here, ε_{zz} is the component of the elastic strain tensor; $\hat{\mathcal{H}}$ the spin-phonon interaction Hamiltonian [11, 12]; $|\psi_m\rangle$ and $|\psi_n\rangle$ are the wave functions of paramagnetic ions in the crystalline field which correspond to the energy levels $\mathcal{E}_m$ and $\mathcal{E}_n$, respectively; G_{33} is the component of the spin-phonon interaction tensor in the Voigt representation [12]; and $\hat{S}_z$ the projection of the vector spin operator onto the z-axis.

In order to estimate Φ_{mn}, let us use the experimentally found value $G_{33} = 5.8$ cm^{-1} $= 1.16 \times 10^{-15}$ erg [14], as well as the wave functions $|\psi_3\rangle$ and $|\psi_2\rangle$ which correspond to the energy levels $\mathcal{E}_3$ and $\mathcal{E}_2$ of Cr^{3+} ions in a trigonal crystalline field of ruby (in this work, similarly to work [5], $m = 3$ and $n = 2$). From Eq. (5), for the magnetic field $H = 3.92$ kOe directed at an angle $\vartheta = \vartheta_{\rm symm}$ with respect to the z-axis, where $\vartheta_{\rm symm} \equiv \arccos(1/\sqrt{3}) = 54°44'$, we find $\Phi_{32} \approx 10^{-15}$ erg. The choice of $\vartheta = \vartheta_{\rm symm}$ was dictated by the requirements of the so-called symmetric (or push-pull) pumping mode which was also used by us earlier to enhance the inversion ratio in a phaser [5]. As a result, at $\nu = 9.1$ GHz, $g(\nu) = 10^{-8}$ s, $C_a = 1.3 \times 10^{19}$ cm^{-3}, $\rho' = 4$ g/cm^3, $V_L = 1.1 \times 10^6$ cm/s, and $T = 1.8$ K, we find from Eq. (4) that $\sigma_{mn} = \sigma_{32} \approx 0.04$ cm^{-1}.

The acoustic Q-factor $Q_C^{(1)}$ for our ruby AFPR (with a piezoelectric film) was measured making use of the pulse-echo method at the frequency $\omega = 9.12$ GHz. The value of $Q_C^{(1)}$ was found to be $(5.2 \pm 0.4) \times 10^5$ at $\vec{H} = 0$ and $P = 0$. Whence, $\eta \equiv \eta_{\rm vol} + \eta_{\rm mirr} = \omega / Q_C^{(1)} V_L \approx 0.1$ cm^{-1}.

In the case of the autonomous phaser, the relation

$$\alpha_g^{(1)} = \eta = K_g \sigma_{32} \quad (6)$$

between σ_{32} and η, where K_g is the critical value of the inversion ratio at the transition $\mathcal{E}_3 \leftrightarrow \mathcal{E}_2$, determines the threshold value $\alpha_g^{(1)}$, at which the generation of the first mode begins. Substituting $\sigma_{32} \approx 0.04$ cm^{-1} and $\eta \approx 0.1$ cm^{-1} into Eq. (6), we find that $K_g \approx 2.5$, which can be ensured liberally by the push-pull scheme of the pumping of ruby.

The autogeneration of longitudinal hypersound in an autonomous phaser was registered provided that external excitations were absent both in the signal and pump channels. The microwave signal of SE emitted by a hypersonic transducer was supplied to a heterodyne spectrum analyzer, and the spectra obtained were photographed immediately from its screen. All power spectra of the phaser generation were measured at $\theta < 2.1$ K, i.e. below the superfluid critical point of liquid helium, which allowed us to avoid the difficulties related to the boiling of this cryogenic liquid.

Now, let us consider the observed spectra of phonon ES in an autonomous phaser generator in detail.

4. Coarse Structure of the Spectra of Stationary Phaser Autogeneration

Since the frequency width Γ_s of the APR line for the spin transition $E_3 \leftrightarrow E_2$ amounts to approximately 100 MHz, and the distance between the AFPR modes is only about 300 kHz, the single-mode SE transforms into a multimode one, even if the excess over the pumping threshold is comparatively small. In other words, there emerges a coarse structure (CS) of the phonon generation (Fig. 1). Provided $\omega_{\rm pump} = \omega_{cp}^{(0)} = 23.0$ GHz and $H = H_0 = 3.92$ kOe, the multimode phonon generation is observed even at $P \geq 50$ μW.

Under the condition of the magnetic-field detuning $\Delta_H \equiv H - H_0 \neq 0$, it is natural that a considerably more intense pumping is needed for the condition $K > K_g$ to be satisfied. On the other hand, the enhancement of a pumping level is also necessary if there is some frequency detuning $\Delta_P \equiv \omega_{\rm pump} - \omega_{cp}^{(0)} \neq 0$.

If the pumping is switched on abruptly, the transient process, which takes place in the course of establishment of the stationary integrated intensity of SE J_Σ, behaves itself oscillatorily. The frequency ω_ν of these damped oscillations (the so-called relaxation frequency) for our system is located, as was already mentioned, in the vicinity of $\omega_\nu/2\pi \approx 10^2$ Hz [8–10]. The lifetime of this transient process $\tau_{\rm tran}$ is shorter than 0.3 s at $P > 0.1$ mW and provided that the magnetic-field and pump-frequency detunings are absent ($\Delta_H = 0$ and $\Delta_P = 0$). Therefore, if the phaser system is finely tuned and the pumping is powerful enough, the transient process is rather fast ($\tau_{\rm tran} \approx \tau_1$). This experimental fact agrees with the estimations of $\tau_{\rm tran} \approx \tau_1/A_P$, where A_P is the pumping parameter (for our system, $A_P \approx 2$ [8–10]), made in the framework of the elementary (balance) model of SE [19]. In other words, under the conditions specified above, the process of formation of the stationary CS of the phaser generation spectra terminates approximately within the same time interval, over which the stationary absorption in a passive (non-inverted) paramagnetic system becomes settled.

5. Regular Fine Structure and Slow Transient Processes in the Microwave Power Spectra

5.1. Emergence conditions for a regular fine structure

At $P \geq 4$ μW, $\Delta_P = 0$, and the small magnetic-field detuning $|\Delta_H| \leq 2 - 3$ Oe, the integral intensity J_Σ of multimode SE of an autonomous phaser, as was already pointed out in work [5], practically does not depend on time. Provided that the frequency tuning is fine as that one and the pumping is powerful enough, the amplitude of J_Σ weakly (in the limits of several percent) oscillates only if $|\Delta_H|$ grows to about 30 Oe [5]. In the non-stationary microwave phonon power spectra, some CS modes of phaser generation become split at $|\Delta_H| \geq 30$ Oe. A typical case of such a splitting for one of the SE modes is quoted in work [5]. Thus, the fine structure (FS) appears for these or other SE modes. The intensities of the FS components $J_F^{(i)}$ in the spectra observed [5] were very low, even at $i_{\max} = 2 \div 3$ (this is several orders of magnitude lower than the intensities of the non-split SE components of stationary generation which are depicted in Fig. 1).

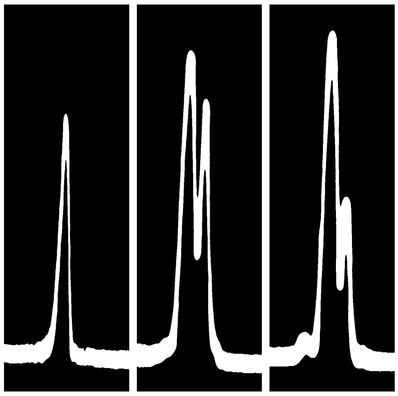

Fig. 2. Emergence of a regular FS in the power spectra of an autonomous phaser at $P = 4$ mW, $\Delta_P = 8.8$ MHz, $\theta = 1.8$ K, and for various $\Delta_H = 0$ (left oscillogram, the FS is absent), 1.5 (middle oscillogram, the two-component FS), and 3.5 Oe (right oscillogram, the three-component FS). The frequency scan width is about 6 kHz for each oscillogram

However, if the system becomes appreciably detuned by the pump frequency ($\Delta_P \gg \Delta_n \approx 0.3$ MHz), the emergence of the FS in the power spectra of phaser generation is observed even at $\Delta_H = 1 \div 2$ Oe. In this case, $J_F^{(i)}$ are of the same order of magnitude as the CS components. In Fig. 2, the splitting of the CS mode into two and three intense FS components, as Δ_H increases from 0 up to 3.5 Oe, is demonstrated (one can also notice very weak additional FS components against the noise background).

5.2. Mechanism of formation of a regular fine structure

The appearance of the regular FS with a few (2–3) components of phonon SE can be explained in the framework of the Casperson—Yariv mechanism [20]. The relative dispersion $\Delta V_L/V_L$ of the phase velocity for hypersound with the frequency ω in a paramagnetic AFPR possessing a certain eigenfrequency of the CS mode $\omega_{cs} \approx \omega$ looks like

$$\frac{\Delta V_L}{V_L} = \frac{\alpha \xi_r}{2k_L(1+\xi_r^2)} = \frac{q_M \xi_r}{(1+\xi_r^2)}, \tag{7}$$

where $\xi_r \equiv (\gamma_s H_0 - \omega)/\Gamma_s$, $\gamma_s = \hbar^{-1}[\partial(\mathcal{E}_3 - \mathcal{E}_2)/\partial H]$, $H_0 = \omega_{cs}/\gamma_s = \pi n V_L/\gamma_s L$, and $q_M = \alpha/2k_L$.

Now, let us introduce the additional detuning of the system by changing the static magnetic field H with respect to its resonant value H_0. Using the dimensionless quantity $h = \gamma_s \Delta_H \Gamma_s^{-1} = (\gamma_s H - \omega_{cs})/\Gamma_s$, we have the following formula for the dependence of the dispersion of the hypersound phase velocity on the magnetic field:

$$\frac{\Delta V_L(h)}{V_L} = \frac{q_M \delta}{(1+\delta^2)}, \tag{8}$$

where

$$\delta \equiv \xi_r + h = \frac{\gamma_s H - \omega}{\Gamma_s}. \tag{9}$$

Now, we apply the well-known Casperson—Yariv relation [20] which couples the refraction index η (in our case, this is the acoustic refraction index $\eta = \eta_{\mathrm{acoust}}$) with the mode frequency $\overline{\omega}$ in the active resonator (in our case, this is a hypersonic mode, for which Eqs. (8) and (9) hold true):

$$(\eta_{\mathrm{acoust}} - 1) L_A \overline{\omega}/L = \omega_{cs} - \overline{\omega}, \tag{10}$$

where L_A is the active medium length. In a phaser, $L_A = L$; therefore, making use of the relation $\Delta V_L/V_L = 1 - \eta_{\mathrm{acoust}}$ and formulae (8) and (9), we obtain the implicit expression for calculating the dependence $\delta(h)$:

$$h - \delta(h) = \frac{q_M \overline{\omega}(h)}{\Gamma_s} \frac{\delta(h)}{1+\delta^2(h)}. \tag{11}$$

On the right-hand side of Eq. (11), we may put $\overline{\omega} = \omega_{cs}$. Then, from Eq. (11) and using the equality $\xi_r = \delta - h$, we find the FS spectrum for the AFPR mode as a function of the magnetic field:

$$\overline{\omega}^{(j)}(h) = \omega_{cs} + \left[h - \delta^{(j)}(h)\right] \Gamma_s. \tag{12}$$

Here, $\delta^{(j)}$ are the roots of the Bonifacio—Lugiato equation

$$h = \left(1 + \frac{2M}{1+\delta^2}\right) \delta, \tag{13}$$

and the quantity M is of the form

$$M = \frac{q_M \omega_{cs}}{2\Gamma_s} \propto \frac{K C_a k_u^2 |\Phi_{32}|^2}{\Gamma_s^2 k_B \theta}. \tag{14}$$

At high h, $\overline{\omega} \to \omega_{cs}$; while at $h \to 0$, $|\overline{\omega} - \omega_{cs}| \propto h$. The intermediate range of h-values, where the function $\delta(h)$ can be multiple-valued, is easily determined with the help of the standard methods of the catastrophe theory. In particular, there are two bifurcations of codimension 2 (at $M = M^{(0)} = 4$ and $h = h_{\pm}^{(0)} = \pm 3\sqrt{3}$) and four bifurcations of codimension 1 (at $M > M^{(0)}$, and $h = h_{\pm}^{(\pm)} = \pm \{(M/2)\,[a(M) \pm b(M)]\}^{1/2}$), where $a(M) = a + 10 - 2a^{-1}$ and $b(M) = [(a-4)^3/a]^{1/2}$. Accordingly, the function $\delta(h)$ can be two-valued at $M = M^{(0)}$ and three-valued at $M > M^{(0)}$.

Therefore, the "static" Casperson—Yariv model considered above demonstrates the mechanism of spontaneous (not connected with external factors) splitting of the CS mode of phonon SE into two or three FS components, depending on the magnetic field. This model can be improved considerably by making allowance for the effects of the type "'hole-burning' in the amplification line" and by considering various dynamic phenomena which were studied earlier in the corresponding branches of nonlinear optics and quantum electronics [20]. Very interesting, in particular, are the issues concerning the very dynamics of formation of the FS in an autonomous quantum generator; especially in the case where the characteristic time of transient processes τ_{tran} is much longer than τ_1. Similar processes of self-induced slowing-down of the evolution have been studied intensively in recent years in nonlinear autonomous systems of various nature, and important theoretical results have already been obtained [15, 16]. In this work, we focus our attention first on the specific issue, namely, whether such slow processes may exist in an autonomous phaser generator or not. The relation between the obtained experimental results and those of theoretical researches [15, 16] will be discussed at the end of the article.

5.3. Slow transient processes at the formation of the regular fine structure

Our observations of the spectra of phonon SE in the autonomous phaser showed that, provided $\Delta_H \neq 0$ and $\Delta_P \neq 0$, the characteristic time of transient processes, which accompany the emergence of the spectral FS, considerably exceeded the time of longitudinal relaxation of Cr^{3+} ions in ruby at the same temperature: $\tau_{\mathrm{tran}}(\theta) \gg \tau_1(\theta)$. For example, for the FS depicted in Fig. 2, $\tau_{\mathrm{tran}}(\theta_0) \approx 30$ s (here, $\theta_0 = 1.8$ K). Not only is this by two orders of magnitude longer than $\tau_1(\theta_0)$, but also is much longer than the transient period for the stationary CS at $\Delta_H = 0$ and $\Delta_P = 0$. Moreover, after the transient process having terminated, the structure of the power spectra is not stationary, as a rule, any more. Instead, there appear periodic oscillations of the intensities of the FS components or even the periodic motions of these components along the frequency axis within the limits of several kHz. These oscillations and motions, as well as the transient process itself, run slowly in comparison to the relaxation time of active Cr^{3+} centers.

At first glance, the anomalously great values of $\tau_{\rm tran}$ in the case of available detunings in the phaser system can be explained as the influence of the slowly relaxing system of Al^{27} magnetic nuclei which belong to the crystalline matrix of corundum. Really, such an influence has been revealed experimentally earlier, when studying the phaser amplification of hypersound in ruby (below the self-excitation threshold of the phaser generation), under conditions $\Delta_H \neq 0$ and $\Delta_P \neq 0$ [13,14]. However, our further researches have demonstrated that, while dealing with the effects of slowing-down the transient processes under the phaser *generation*, this mechanism does not dominate.

Really, the slow motions, which were observed in the integrated electron-nuclear system of ruby [13, 14], are characterized by the well-known restriction on the maximal lifetime of the transient process $\tau_{\rm tran}$ in this system – the relaxation time $\tau^{(z)}_{\rm nucl}$ of the Zeeman reservoir for the subsystem of magnetic nuclei [21, 22]. Under our experimental conditions, $\tau^{(z)}_{\rm nucl}$ does not exceed 10 s, which is three times shorter than the values of $\tau_{\rm tran}$ observed at the FS formation in the power spectra of the phaser generation.

More detailed researches of the power spectra of an autonomous phaser demonstrated that, under definite conditions, the FS formation can occur following much more complicated scenarios than those in the experiments described above. In this case, the ultimate state of the SE line turns out qualitatively different from what is shown in Fig. 2, and the lifetime of the transient process grows substantially ($\tau_{\rm tran} > 10^2$ s). A similar situation arises, e.g., if, provided $\Delta_P \gg \Delta_n$, the parameter Δ_H becomes several times still larger with respect to those Δ_H values, for which the FS shown in Fig. 2 was observed. Let us consider these experiments in detail.

6. Super-slow Transient Processes and Selective Fine Structure Randomization of Microwave Power Spectra

6.1. Observation of the selective fine structure randomization

Provided the same corresponding values for P (4 mW) and Δ_P (8.8 MHz) as in the previous experiments, but for the enlarged magnetic-field detuning up to Δ_H = 15 Oe, the regular FS which is shown in Fig. 2 was found to be gradually destroyed. In approximately 10 min after the indicated detuning having been introduced, its form became chaotic. In this work, we use the term "chaotic FS", not specifying the character of disorder, because it is still not clear, whether this is a deterministic chaos, as the processes observed earlier in non-autonomous phasers are [8–10], or some kind of the small-scale spin-phonon turbulence emerges. The data presented below allow us to assert only that the dimension of the phase space, which is necessary to describe the observed chaotic FS, should be much higher than that in the case of the ordinary low-dimension deterministic chaos which was studied in phasers with periodic pump modulation [8–10].

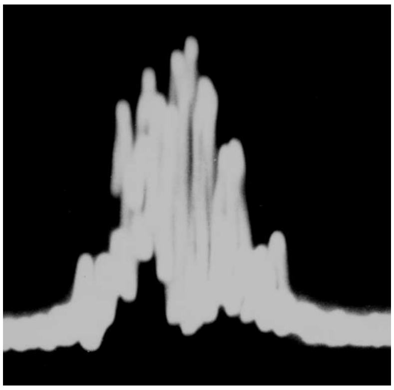

Fig. 3. Chaotic FS of the phonon generation at P = 4 mW, Δ_P = 8.8 MHz, θ = 1.8 K, and Δ_H = 15 Oe. The frequency scan width is about 18 kHz

A typical pattern of the chaotic FS in an autonomous phaser is shown in Fig. 3. Unlike the regular FS which can be either static or periodically pulsing, the chaotic FS is distinguished for fast, irregular, and non-synchronized pulsations of the amplitudes of its numerous components, and these pulsations are accompanied by similar irregular and non-synchronized motions of the components along the frequency axis.

From Fig. 3, one can see that the width of such a randomized FS line is several times greater than the width of the line with a regular FS. Holding Δ_P = 8.8 MHz and Δ_H = 15 Oe constant, but reducing the pump power by a factor of four, a diminishing of the maximal intensities of the chaotic FS components is observed, as well as some narrowing of the FS line as a whole (Fig. 4).

The further reduction of P results in suppressing the phonon generation at the randomized SE mode, with the structure of the latter becoming somewhat ordered near the suppression threshold ($P \approx 0.1$ mW).

The suppression of the generation for the chaotic SE mode may happen at fixed P as well, but when varying Δ_P or Δ_H. In so doing, contrary to the case of reducing

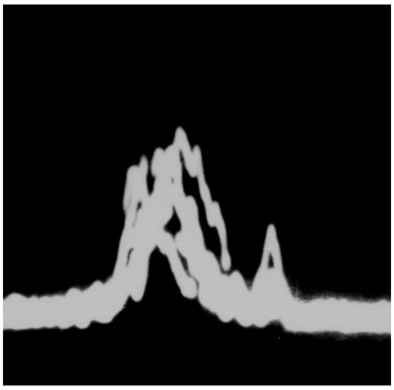

Fig. 4. The same as in Fig. 3, but at $P = 0.9$ mW

P, the randomization of one of the neighbor CS modes, which has not been split at all till then, is often observed. It is essential that similar effects take place only in the rather narrow "windows" of Δ_P and Δ_H detunings. Beyond the limits of these "windows", the complete randomization of the FS components is not achieved, but some intermediate states of the SE mode splitting take place outside such windows as well. For example, the FS line can possess a few components (2—3), which pulse smoothly by amplitude and move asynchronously along the frequency axis (within an interval of ± 10 kHz). An example of such an intermediate FS state in the case $\Delta_H \approx 30$ Oe was already cited by us in work [5].

6.2. Superslow transient processes at fine structure randomization

It should be emphasized that although the pulsations of chaotic FS components are fast enough for a certain fixed set of the control parameters, but *transitions* from one chaotic state to another (for example, between those shown in Figs. 3 and 4) proceed even more slowly than in the case of transitions between various states of a regular FS. Typical values of τ_{tran} for transitions between the states of a chaotic FS amount to $\tau_{\text{tran}} \gtrsim 10^3$ s, which can be confronted with the times of superslow motions of the non-autonomous phaser system observed earlier in work [5].

However, at this point, the similarity between superslow processes in autonomous and non-autonomous generators comes to the end. For the autonomous phaser, the emergence of superslow motions is a characteristic feature of the whole power spectrum (the typical width of the spectrum amounts to several MHz). In this case, the "outburst" of CS modes on one side of the spectrum, accompanied by the "fading" of approximately the same number of CS modes on its other side, takes place. Similar processes arise only in the range of the nonlinear resonance of a phaser system stimulated by the deep modulation of the pumping [5].

Of the autonomous phaser, typical are the scenarios, when the majority of CS modes are almost stationary. Only the rest one or two modes behave in a very complicated fashion at certain combinations of the control parameters. The modification of such a combination of the control parameters is needed in order that such a complicated behavior may transform into one of the quasi-stationary modes. A similar selective destruction of the coherent SE modes, as well as the very fact of the coexistence of stationary and non-stationary states in the active medium of the phaser, demands that the spatial effects of spin-phonon interaction should be considered, taking into account the microscopic processes of energy exchange between individual active centers. Certainly, the solution of such a problem requires a separate article, but some preliminary results towards this direction can be obtained in the framework of the simplified model of the phaser active medium which has recently been proposed in work [23]. Below, the spatial effects and the transient processes, which were observed in the computer simulation experiments [23], as well as their relation to the results of real experiments carried out at an autonomous phaser, will be discussed shortly. But first, it is necessary to stop at some conceptual moments dealing with phaser models.

6.3. Macro- and microscopic approaches to simulating the transient processes in systems of the phaser type

Slow transient processes at the phaser *amplification* of hypersound (below the threshold of the phaser self-excitation) were observed else in the 1970—1980s [13,14]. The characteristic time of those processes did not exceed, as was said above, the relaxation time of Al^{27} nuclei which constitute an additional energy reservoir in the phaser active medium. This reservoir interacts with the electron spin subsystem of the active chromium centers in the crystalline matrix of Al_2O_3 owing to a thermal contact between the system of Al^{27} nuclei and the electron dipole-dipole ($d - d$) reservoir made up by Cr^{3+} ions [21]. Such a contact is possible due to the proximity of the nuclear magnetic resonance (NMR) frequencies of Al^{27} to the characteristic frequencies of electron $d - d$ interactions in the system of Cr^{3+} ions (all these frequencies are of the order of 10 MHz). As a result, the slowing-down evolution of the integrated electron-nucleus system of a phaser amplifier can be described adequately [13, 14] in the framework of the nonequilibrium spin thermodynamics concepts [21].

It is known that those concepts are based on the hypothesis about the so-called spin temperatures [21, 22], i.e. some macroscopic characteristics of the energy reservoirs of a nonequilibrium quantum-mechanical system, the saturation of which is ensured by an external coherent dc field close to one of the system's resonances (NMR, ESR, or APR). We emphasize that it is the fact of saturating the system by an external resonant field that enables us to analyze the distribution of spin level populations in the coordinate system which "rotates" synchronously with the frequency of the applied field. Under rather general conditions, such a distribution is exponential, which allows us to speak about such a macroscopic parameter as the spin temperature of one or another energy reservoir.

Absolutely different is the situation, when various modes of phaser *generation* emerge, evolve, and stabilize. Especially, this concerns the multimode operation. Really, even provided that the FS is absent, the spin system of a phaser generator becomes saturated not only due to the pump field, but also to the fields of its intrinsic multimode signal at the CS frequencies (see Fig. 1), because the single-mode generation turns out unstable. In this case, individual reservoirs and, correspondingly, individual spin temperatures for every CS mode have to be considered.

Again, the occurrence of a regular FS (Fig. 2) not only increases the number of macroscopic parameters, which are necessary for the description of the active system behavior, but also calls into question the adequacy of such a thermodynamic approach in general. Concerning the appearance of the chaotic FS of a phaser generator (Fig. 3), the macroscopic model of spin thermodynamics [21, 22], which yielded the satisfactory results for a phaser amplifier [13, 14], becomes obviously unacceptable now, beyond any doubts. In order to understand the mechanisms of formation of the chaotic FS (including such issues as the slowing-down of transient processes, the coexistence of regular and randomized CS modes, and so on), we have to deal with the simulation of inversion states of the phaser system at the microscopic level.

Carrying out the direct (imitation) simulation of the evolution of the inverse states of an active system on the basis of the system of Maxwell—Bloch coupled equations [24] becomes inexpedient even at the number of active centers $N \gtrsim 10^3$, because too huge computational resources would be required for this purpose. Alternative is the way to apply discrete models of the cellular-automat type [25]. Such models use the algorithms with local information processing (K- or Kolmogorov algorithms [26]) and allow the program to run effectively on ordinary personal computers even if $N \gtrsim 10^6$. It is important that K-algorithms in such cellular-automat models belong to the polynomial (by time) P-class of complexity [27], which allows N to be increased further by several orders of magnitude for middle-class computers.

6.4. Possibility of the formation of a self-organized bottleneck in active systems of the phaser type

In work [23], the computer simulation of the excited states evolution in a nonequilibrium class-B system with the diffusive mechanism of energy exchange between active centers was carried out. The relevant K-algorithm was constructed on the basis of the excited medium model of the Wiener—Rosenbluth type [28]. The possibility of using such an excited medium in the simulation of quantum generators of class B in the case of a continuous active system was pointed out earlier [29,30]. A discrete model [28], as well as its generalization used in work [23], allows the direct projection onto the computer architecture (unlike continuous models) to be made. It also increases the rate of iterative processes considerably, especially for large N.

The results of computer simulations showed [23] that a typical scenario of the evolution of an autonomous system of class B with weak diffusion of excitations is the formation of coherent vortex-like structures of the rotating spiral wave (RSW) type. The creation, motion, interaction, and destruction of RSWs in the case where the parameters of active centers are close to the corresponding parameters of paramagnetic ions in phasers demonstrate the attributes typical of self-organization, which, nevertheless, differ substantially from those inherent to the self-organization in a *non-autonomous* phaser system excited by an external force in the range of some of its nonlinear resonances [5, 7].

In particular, as was found in work [23], the global character of the evolution of an autonomous system is governed only by its intrinsic parameters and depends very weakly on the initial spatial distribution of excitations among active centers. The evolution may bring about the relatively simple states of the active system, which include a few (or even a single one) RSWs, as well as the states, where the motion of a huge number of RSWs is organized in a very complicated manner. However, in most cases studied in work [23], the typical lifetime of transient processes in the system of interacting active centers turned out considerably (by many orders of magnitude) longer than the maximal relaxation time of isolated active centers.

In contrast to the known effect of a non-coherent PB (which, as was already pointed out earlier, is not present in ruby phasers), we deal here with the substantial enlargement of transient process lifetimes due to the very slow structuring and development of *coherent* RSWs. In some aspects, these nonlinear phenomena that were observed in computer experiments [23] are similar to the effects of a self-organized bottleneck (or the self-induced slowing-down of transient processes) which were discovered in both the system of interacting oscillators [15] and a system of the reaction-diffusion type [16]. In contrast to the model [15], active centers in the model of the excited medium [23] are not oscillators. Therefore, the features of a self-organized bottleneck differ very substantially for an active system of class B [23] from what was observed in studies [15]. Much closer to the model of the excited medium [23] is the system of the reaction-diffusion type, used in work [16] (the latter is a modification of the well-known "Brusselator" [31]), although, certainly, the essential differences in the corresponding mechanisms of non-linearities are available here as well. However, it is of importance that, despite different mechanisms of non-linearity, the very fact of the huge slowing-down of transient processes, provided that the self-organization of one or another state takes place in the autonomous system, is the common point for all the three works [15, 16, 23].

Hence, plausible looks the assumption that the phenomenon of a self-organized bottleneck, analogous to that observed in computer simulation experiments for an active system of class B [23] and close to the phenomena simulated in works [15, 16], may be responsible for the slowing-down of the transient processes in a phaser. The additional evidence for this assumption is the results of simulations of the effect of coexistence between regular and chaotic spatial structures [23] which correlates with the coexistence between the regular and chaotic FS modes of the phaser generation described above. Certainly, the possibility for coherent structures of the RSW type to exist in a real phaser system still demands additional researches, although helical structures have already been observed in dissipative nonlinear-optical systems [2, 3].

A particular emphasis should be made that, as was already pointed out in work [15], the self-organized bottleneck has the origin qualitatively different from that of the well-known phenomenon of self-organized criticality [32]. The latter arises only in non-autonomous systems (as a response to an external destabilizing force), whereas the self-organized bottleneck [15, 16, 23] is a result of internal processes running in the autonomous system itself.

In this aspect, the effects of self-organization experimentally observed in non-autonomous (previous works [5, 7]) and autonomous (this work) phasers may also be examined from qualitatively different points of view. Really, slow self-organized motions in the spin-phonon system of a non-autonomous phaser [5, 7] arise just under the influence of an external resonant destabilizing force and disappear after switching the latter off. The absolutely different picture was observed in this work for autonomous phasers, because here the slowing-down of the transient processes is self-induced and requires no additional external perturbations. On the other hand, in the case of a non-autonomous system similar to that described in works [5,7], the slow motions continue as long as the corresponding destabilizing force is active, while the transient process in an autonomous system has, of course, an entirely definite (though, probably, very long) characteristic time. As we have shown in this work, the ultimate state of an autonomous phaser need not necessarily be regular, because the FS may possess a very complicated (though, probably, even deterministic) structure, the detailed investigation of which is perspective for continuing the researches in this direction.

7. Conclusions

The processes of the FS formation in the power spectra of a ruby-based autonomous phaser generator (Cr^{3+}:::Al_2O_3) have been studied. Experimentally, the lifetime τ_{tran} of transient processes occurring when a regular FS is formed was revealed to be two orders of magnitude longer than the time of longitudinal relaxation τ_1 of Cr^{3+} ions, if the phaser system is appreciably detuned by both the pump frequency and the magnetic field. The further increase of detuning leads to the selective randomization of the FS, when the number of FS components considerably increases for some modes of the phonon SE, with these components varying irregularly by both their amplitudes and frequencies. The transitions from one chaotic state to another are slower than even the transitions between various states of a regular FS. The typical values of τ_{tran} for the transitions between the states of a chaotic FS are $\tau_{\text{tran}} \gtrsim 10^3$ s. The emergence of a regular FS can be explained in the framework of the known Casperson-Yariv model [20].

The possible mechanisms of the emergence of a selective chaotic FS, the coexistence between the regular and chaotic states, and, especially, the nature of superslow transient processes in an autonomous phaser have been discussed. The effects of slowing-down the transient processes have been revealed recently, when simulating numerically the discrete excited active systems [23] which can be regarded as analogs, to a certain extent, of active media of class-B quantum generators [29, 30]. A typical evolution scenario of such systems is the formation and the slow development of complicated coherent autostructures. The formation of a bottleneck in the course of self-organization of spatial structures, which leads, as the computer simulation testifies [23], to the huge slowing-down of transient processes, may have the direct relation to the slowing-down effects that were observed experimentally in this work for an autonomous phaser.

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УПОВІЛЬНЕННЯ ПЕРЕХІДНИХ ПРОЦЕСІВ ПРИ ФОРМУВАННІ ТОНКОЇ СТРУКТУРИ У СПЕКТРАХ ПОТУЖНОСТІ МІКРОХВИЛЬОВОГО ФОНОННОГО ЛАЗЕРА (ФАЗЕРА)

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Р е з ю м е

Досліджено процеси формування регулярної та хаотичної тонкої структури (ТС) у спектрах потужності автономного фононного лазера (фазера). Експериментально спостережене значне уповільнення перехідних процесів при формуванні ТС в умовах розстроювання по магнітному полю та частоті накачки. Запропоновано пояснення спостереженого уповільненя на основі моделі самоорганізованої вузької горловини, розвинутої раніше для розподілених збуджуваних систем, що емулюють динаміку лазерів класу B.