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CONTROL OF LASER RADIATION PARAMETERS

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Spectral nonreciprocity induced by a magnetic field in nonstationary lasing regimes of a solid-state ring laser

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***Abstract*. It is found experimentally that the application of a magnetic field to the active element of a monolithic ring Nd : YAG chip laser in nonstationary lasing regimes can result in nonidentical spectral parameters of counterpropagating radiation waves (spectral nonreciprocity) in quasi-periodic and chaotic lasing regimes. The value of the spectral nonreciprocity depends on the coupling coefficient of counterpropagating waves, the excess over the pump threshold, and the optical nonreciprocity of the ring cavity. The obtained results are in good agreement with the results of numerical simulation.**

Keywords: *solid-state ring laser, spectral nonreciprocity, nonlinear dynamics, dynamic chaos.*

1. Introduction

A solid-state ring laser is a self-sustained oscillatory system, which can have complex dynamics even in the case of single-mode lasing in each of the opposite directions. It is important that counterpropagating waves in a ring laser are not independent but they interact with each other due to linear and nonlinear coupling between them. Linear coupling is caused by unavoidable backward scattering from inhomogeneities of the reflecting surfaces of the ring cavity and the active medium itself. Nonlinear coupling of counterpropagating waves is caused by their self-diffraction from the inverse population gratings induced by the waves themselves in the active medium. The amplitude and frequency nonreciprocity of a ring cavity also affect the interaction between counterpropagating waves [1, 2]. This interaction induces self-modulated lasing regime of the first kind in an autonomous solid-state ring laser over a wide range of parameters. The spectra of self-oscillating intensities of counterpropagating waves are identical in this regime.

The situation is quite different in a non-autonomous solid-state ring laser: in this case, modulation of its parameters may lead to lasing regimes in which the time characteristics and intensity spectra of counterpropagating waves are different. It is interesting to study the nonidentity of spectral parameters of these waves in nonstationary lasing regimes, including the dynamic chaos regime which has been the subject of intense investigations in recent times (see, for example, Refs [3 – 9]). Interest in this problem is also stimulated by the possibility of practical applications of the dynamic chaos in optical communication and measuring technique [10, 11].

In nonstationary lasing regimes, the intensity and optical phase oscillations of counterpropagating waves may be mutually correlated or uncorrelated. As a rule, the behaviour of intensities of counterpropagating waves is studied, although information about the phase dynamics of radiation can also be obtained in some cases (see, for example, Refs [6, 7]). Note that although, in principle, no correlation can exist between the intensities of counterpropagating waves in dynamic chaos regimes, their oscillations can be synchronised in phase, which is manifested in a variation of the phase difference between counterpropagating waves over a finite interval (the phase difference does not increase linearly in time) [12]. It is expedient to analyse the correlation of spectral parameters of the intensities of counterpropagating waves to obtain detailed information about the dynamics in nonstationary lasing regimes of these waves.

The difference in the spectral characteristics of counterpropagating waves in a ring laser can be analysed with the help of the concepts used in optics for studying nonreciprocal optical effects. We shall call the difference in the spectral characteristics of counterpropagating waves the spectral nonreciprocity [13]. Note that the possibility of its emergence in solid-state ring lasers during harmonic modulation of the perimeter (length) of the resonator was reported in earlier papers [14, 15]. For example, lasing regimes with a different type of modulation of the intensities of counterpropagating waves were observed in Ref. [14] during modulation of the laser cavity perimeter at frequencies $\omega_p/2\pi \sim 100$ Hz.

In this work, we present the results of experimental and theoretical investigations of the conditions of emergence as well as certain parameters determining the spectral nonreciprocity of counterpropagating waves in a highly stable ring chip laser upon modulating its parameters (mechanical stresses in the active element). Modulation of mechanical stresses is accompanied by a variation in the optical length of the resonator, birefringence (resulting in losses inside the polarisation-anisotropic ring cavity), as well as detuning of

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lasing frequency from the gain line centre. Results of numerical simulation show (see below) that modulation of birefringence has the most significant effect on the radiation dynamics.

2. Experimental setup

The experiments were made on a setup identical to the one described in Ref. [16], where the modulation of parameters was carried out by deforming the optical contour of the cavity with the help of a piezoelement. A monolithic ring Nd:YAG chip laser with a nonplanar cavity (with a nonflatness angle ~ 80°) operating in a single-frequency mode was investigated. The perimeter of the cavity was 2.6 cm. The chip laser was pumped by a 0.5-W, 0.810-μm semiconductor laser diode. The piezoelement produced periodic mechanical stresses in the active element of the chip laser. The modulation frequency $\omega_p/2\pi$ of these stresses could be varied from 20 to 200 kHz, while the voltage U applied to the piezoelement and determining the modulation depth h of mechanical stresses was varied from 5 to 30 V. The magnetic field was produced with the help of a permanent micromagnet. Its strength H and orientation relative to the symmetry plane of the active element were varied by displacing the micromagnet. The strength H of the field was determined from the variation in the self-modulation frequency $\omega_m/2\pi$.

The experimental setup was capable of recording simultaneously the intensities I_1 and I_2 of counterpropagating waves and their spectra with the help of an ACK-3151 digital oscilloscope. By processing the experimental results we obtained Pearson correlation coefficients [17], which were used to determine the nonidentity of temporal and spectral characteristics of counterpropagating waves:

$$K(I_1, I_2) = \frac{\sum\limits_{i=1}^{n}(I_{1i} - \bar{I}_1)(I_{2i} - \bar{I}_2)}{\left[\sum\limits_{i=1}^{n}(I_{1i} - \bar{I}_1)^2(I_{2i} - \bar{I}_2)^2\right]^{1/2}},$$

where $\bar{I}_{1,2}$ are the mean values of the variables I_1 and I_2.

3. Experimental results

In the absence of modulation and magnetic field, a single-frequency self-modulation lasing regime of the first kind was observed in the laser. The self-modulation frequency was $\omega_m/2\pi = 145$ kHz, while the relaxation oscillation frequency was $\omega_r/2\pi = 79$ kHz when the excess of the pump power over the threshold was $\eta = 0.3$.

Our investigations show that periodic, quasi-periodic and chaotic lasing regimes similar to those emerging during the pump power modulation [18–20], appeared, as a rule in a wide range of modulation parameters $\omega_p/2\pi$ and h. Note that despite certain differences in the temporal characteristics, the spectral parameters of these regimes are almost identical. For example, for a modulation frequency $\omega_p/2\pi = 89$ kHz, a modulation depth corresponding to an alternating voltage $U = 20$ V and $\eta = 0.32$, a chaotic lasing regime emerges in the laser, where the radiation of counterpropagating waves is a train of pulses whose amplitude and repetition rate are chaotic by nature. This can be seen clearly from the oscillograms of radiation of counterpropagating waves and the projection of the phase portrait in the I_1, I_2 plane (Figs 1a, b). The intensity spectra of counterpropagating waves (Fig. 1c) consisting of many components remain practically identical in this regime (i.e., there is no spectral nonreciprocity in this case).

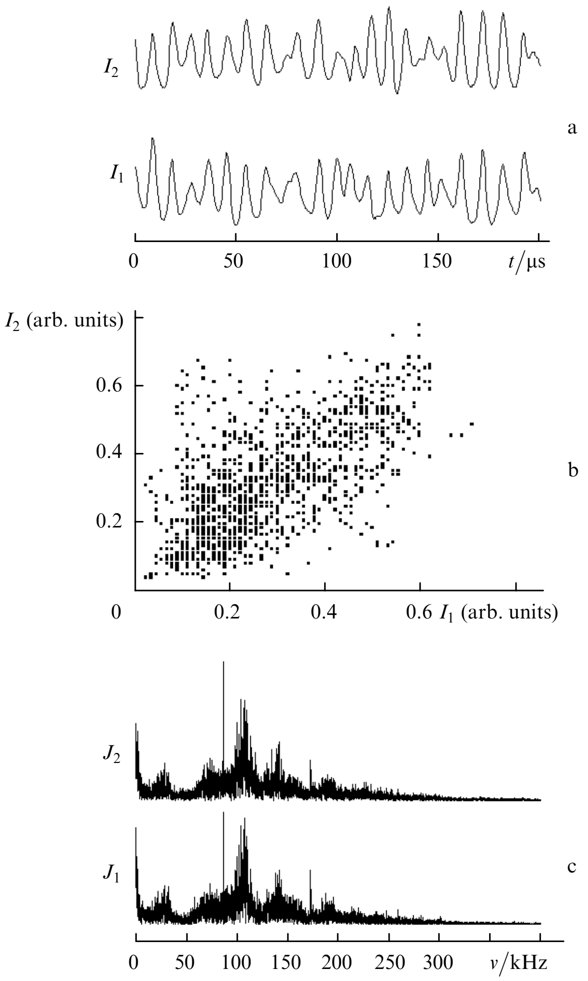

Figure 1. Nonsynchronous dynamic chaos regime for counterpropagating waves modulated by mechanical stresses: (a) intensities I_1, I_2, (b) phase portrait in the I_1, I_2 plane, and (c) spectra of counterpropagating waves J_1, J_2 ($\nu = \omega/2\pi$).

For a modulation frequency of mechanical stresses lying in the vicinity of the relaxation frequency ($\omega_p/2\pi = 72$ kHz) and a small modulation depth h corresponding to $U = 8$ V, quasi-periodic lasing regimes appear, which are also characterised by unequal intensities of counterpropagating waves and by nearly identical spectra. The situation changes radically when the optical ring cavity acquires nonreciprocity after the application of a constant magnetic field H to the active element. For $H = 52$ Oe (the micromagnet axis was parallel to one of the faces of the ring cavity and its centre was outside the symmetry plane of the active element), a quasi-periodic lasing regime appeared (Figs 2a, b) and both the intensity and spectra of counterpropagating waves (Fig. 2c) became different. One can see that transition from a chaotic to a quasi-periodic lasing regime is accompanied by the emergence of spectral nonreciprocity: the structures of the spectra of counterpropagating waves prove to be different in this case.

Note that the necessary conditions for the emergence of spectral nonreciprocity are the modulation of mechanical stresses and the application of a constant external magnetic

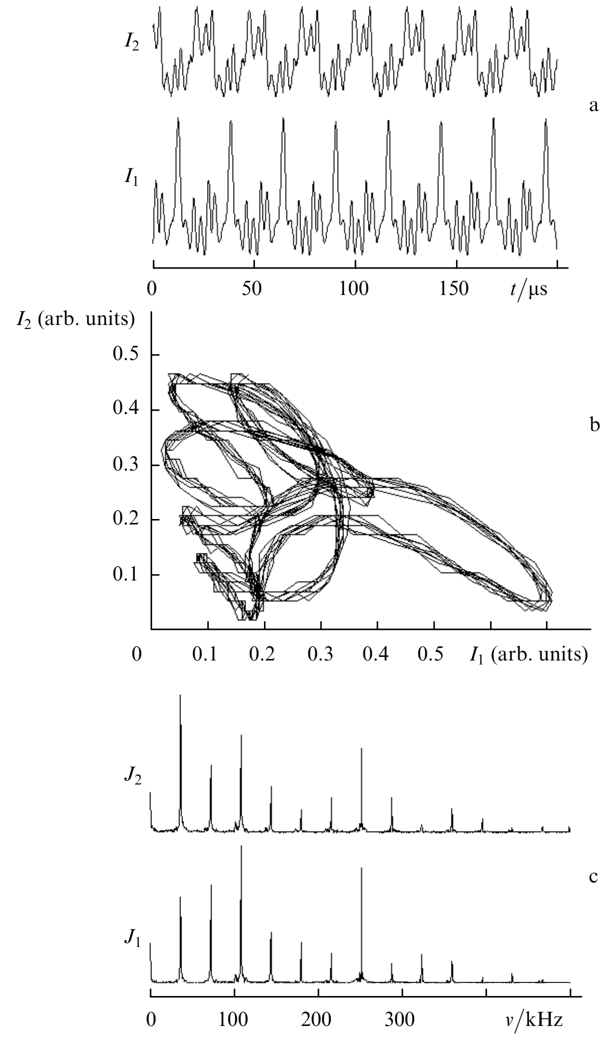

Figure 2. Quasi-periodic regime with unequal intensities and spectra of counterpropagating waves (experiment) modulated by mechanical stresses: (a) intensities I_1, I_2, (b) phase portrait in the I_1, I_2 plane, and (c) spectra of counterpropagating waves J_1, J_2.

field that leads to the emergence of the frequency (phase) and amplitude nonreciprocities in the cavity. When any of these conditions is not fulfilled, either a quasi-periodic regime with almost identical spectra of counterpropagating waves is observed or a self-modulation regime of the first kind with $\omega_{\rm m}/2\pi = 208$ kHz.

Our study has shown that the lasing regimes characterised by the presence of spectral nonreciprocity exist in a rather narrow range of parameters $\omega_{\rm p}/2\pi$, h, and H, which apparently means that they have a parametric nature [21, 22]. Thus, for the pump power excess over the threshold $\eta = 0.48$ and for a modulation frequency $\omega_{\rm p}/2\pi = 77$ kHz, the spectral nonreciprocity regime is preserved upon a variation in the modulation depth h ($U = 16.5 - 30$ V). For a fixed value of h ($U = 17$ V), the modulation frequency of intracavity losses may vary in the interval 76–80 kHz.

The spectral nonreciprocity was characterised quantitatively in nonstationary regimes using the Pearson correlation coefficients $K[I_1(t), I_2(t)]$ и $K[J_1(\omega), J_2(\omega)]$ for the intensities of counterpropagating waves and their spectra respectively [17]. It was found that in the absence of spectral nonreciprocity, the correlation coefficient $K[J_1(\omega), J_2(\omega)]$ is close to unity, while its value differs significantly from unity in the case of spectral nonreciprocity. Note that the intensity correlation coefficients $K[I_1(t), I_2(t)]$ are close to each other in both regimes and differ significantly from unity.

Note that we obtained similar results for a chip laser ($\omega_{\rm m}/2\pi = 230$ kHz) pumped by modulated radiation.

4. Results of numerical simulation

We also simulated numerically the nonlinear dynamics of radiation emitted by a ring chip laser using the standard model of a solid-state ring laser [1, 2]. The parameters of the model (except the modulation depth h) were found to be close to the parameters of the laser under study, and the modulation depth of losses was varied from 0.01 % to 0.1 %. An agreement with the experiment was reached for $h = 0.04$ %. It was assumed that during modulation of mechanical stresses in the active medium of the chip laser, the modulation of counterpropagating wave losses occurs due to birefringence in this medium and the presence of polarisation anisotropy of the ring cavity.

Thus, the numerical simulation showed that for $H = 53$ Oe, $\eta = 0.38$, $\omega_{\rm p}/2\pi = 79$ kHz and $h = 0.04$, nonstationary lasing regimes with spectral nonreciprocity appear in a ring laser, which are similar to the experimentally observed lasing regime. Figure 3 shows the

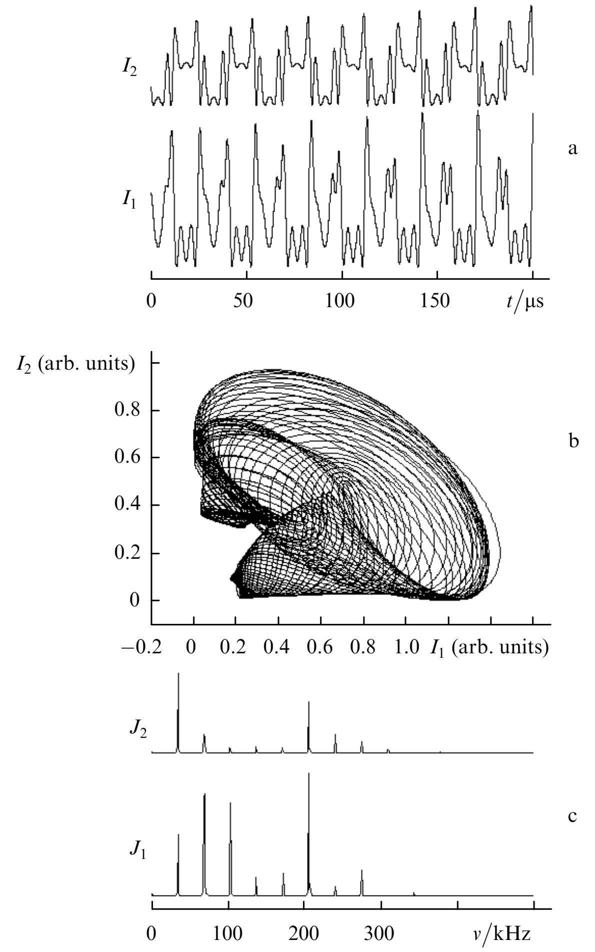

Figure 3. Quasi-periodic regime with unequal intensities and spectra of counterpropagating waves (numerical simulation) modulated by mechanical stresses: (a) intensities I_1, I_2, (b) phase portrait in the I_1, I_2 plane, and (c) spectra of counterpropagating waves J_1, J_2.

characteristic time and spectral realisations obtained during numerical simulation. We also calculated Pearson correlation coefficients and compared their values with those measured experimentally. These results are presented in Table 1.

Table 1. Correlation coefficients for intensities of counterpropagating waves and their spectra without and with spectral nonreciprocity.

Lasing regime	$K[I_1(t), I_2(t)]$	$K[J_1(\omega), J_2(\omega)]$
Without spectral nonreciprocity (Fig. 1)	0.56	0.98
With spectral nonreciprocity (Fig. 2)	0.30	0.509
With spectral nonreciprocity (numerical simulation, Fig. 3)	0.308	0.686

5. Conclusions

Thus, our experimental studies and the results of numerical simulation of the dynamics of a solid-state ring laser with a periodic modulation of mechanical stresses in the active element have shown that nonstationary lasing regimes with spectral nonreciprocity of radiation of counterpropagating waves may appear in such a laser. It is found that such regimes emerge in a laser with a periodic modulation of parameters only in the case of optical nonreciprocity in a ring cavity. Identification of such regimes (i.e., the evaluation of quantitative differences in the characteristics of counterpropagating waves) can be carried out by using the correlation coefficients of intensities of counterpropagating waves and their spectra.

Further investigations in this field are of interest for studying the nonlinear dynamics of ring lasers and for measuring optical nonreciprocities.

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