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Evolution of transient oscillation regimes in monolithic ring lasers

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***Abstract*.** **The evolution of the regions of existence and stability of quasi-periodic and chaotic oscillation regimes in a monolithic ring Nd : YAG laser caused by changing the pump power is studied experimentally. It is shown that the dynamic chaos regime appearing upon modulation of the pump power is alternated by windows in which different quasi-periodic lasing regimes take place. A scenario of the passage from the self-modulation lasing regime to dynamic chaos is considered.**

Keywords: *ring solid-state laser, nonlinear dynamics, dynamic chaos, transient processes.*

1. Introduction

Highly stable diode-pumped monolithic ring Nd:YAG lasers (ring chip lasers) are now widely used both in fundamental studies in the field of laser physics and in laser technologies. Applications of such lasers have shown that their functional possibilities are far from being exhausted, so it is not surprising that investigations of the nonlinear radiation dynamics of these lasers, which allow the better understanding of the peculiarities of interaction between optical waves in an amplifying medium, attract great interest.

Quasi-periodic and chaotic regimes in ring lasers caused by external periodic perturbations have not been adequately studied so far. Although these regimes were investigated in many papers [1 – 12], a number of important practical problems still remain to be solved. Among these problems is, in particular, the study of evolution of the region of existence of different quasi-periodic and chaotic lasing regimes in monolithic ring chip lasers as a function of the excess over the lasing threshold.

In this paper, we studied the features of the nonlinear radiation dynamics of monolithic ring Nd : YAG lasers in transient oscillation regimes and the conditions of the appearance of quasi-periodic and chaotic oscillation regimes. The evolution of these regimes upon variation of control parameters in a broad range is also investigated.

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2. Experimental

We used the experimental setup that was similar to that described in [12]. The active element of a ring laser under study was a high-quality Nd^{3+} : YAG crystal in the form of a polyhedral prism with one spherical face and three faces providing, due to total internal reflection, the existence of a closed nonplanar trajectory for counterpropagating light waves. The geometrical perimeter of the ring resonator was 2.6 cm and the nonplanarity angle was 80°. The laser was pumped by a laser diode with a power supply providing not only continuous variation of the pump power but also its modulation in a broad frequency range from 10 to 90 kHz. The modulation amplitude h could achieve in this case 100 %. The laser temperature was stabilised with an accuracy of $\sim$0.05°.

The radiation of counterpropagating waves and a signal obtained upon their mixing were incident on broadband LFD-2 photodetectors connected to a four-channel Tektronix TDS-2014 oscilloscope. The radiation intensities $I_{1,2}$ of counterpropagating waves, their spectra $J_{1,2}$, and photomixing signals $I_{\rm mix}$ could be recorded simultaneously in experiments.

3. Experimental results

The coupling of counterpropagating waves in the ring laser was symmetrical (the moduli of the coupling coefficients of counterpropagating waves were $|m_1| = |m_2| = |m|$) and the self-modulation regime of the first kind existed in the chip laser in the absence of pump modulation. The value of $|m|$ determined from the self-modulation frequency $\omega_{\rm a}/2\pi$ was 180 kHz, while the relaxation oscillation frequency $\omega_{\rm r}/2\pi = (\omega\eta/QT_1)^{1/2}$ (where Q is the resonator Q factor and T_1 is the relaxation time of the metastable level), depending on the resonator losses, was 90 kHz for $\eta = 0.1$.

With the modulation depth $h = 20\,\% - 70\,\%$ in a narrow range of low modulation frequencies ($\omega_{\rm p}/2\pi \leqslant 5$ kHz), the self-modulation quasi-sinusoidal oscillation regime with the low-frequency intensity modulation was developed in the laser (the QS-1 regime). In this case, the emission spectrum consisted of two components at frequencies $\omega_{\rm p}/2\pi$ and $\omega_{\rm a}/2\pi$. As the modulation frequency was increased up to a critical value, which depended on the modulation depth and was equal $\sim$5 kHz, the dynamic chaos regime appeared in the laser, which was interrupted by the regions of existence of quasi-periodic regimes with different radiation pulse repetition rates. As the modulation frequency was increased, first the regime appeared in which the quasi-periodic pulse repetition rate was $\omega_{\rm p}/2\pi$, then the regime with a pulse

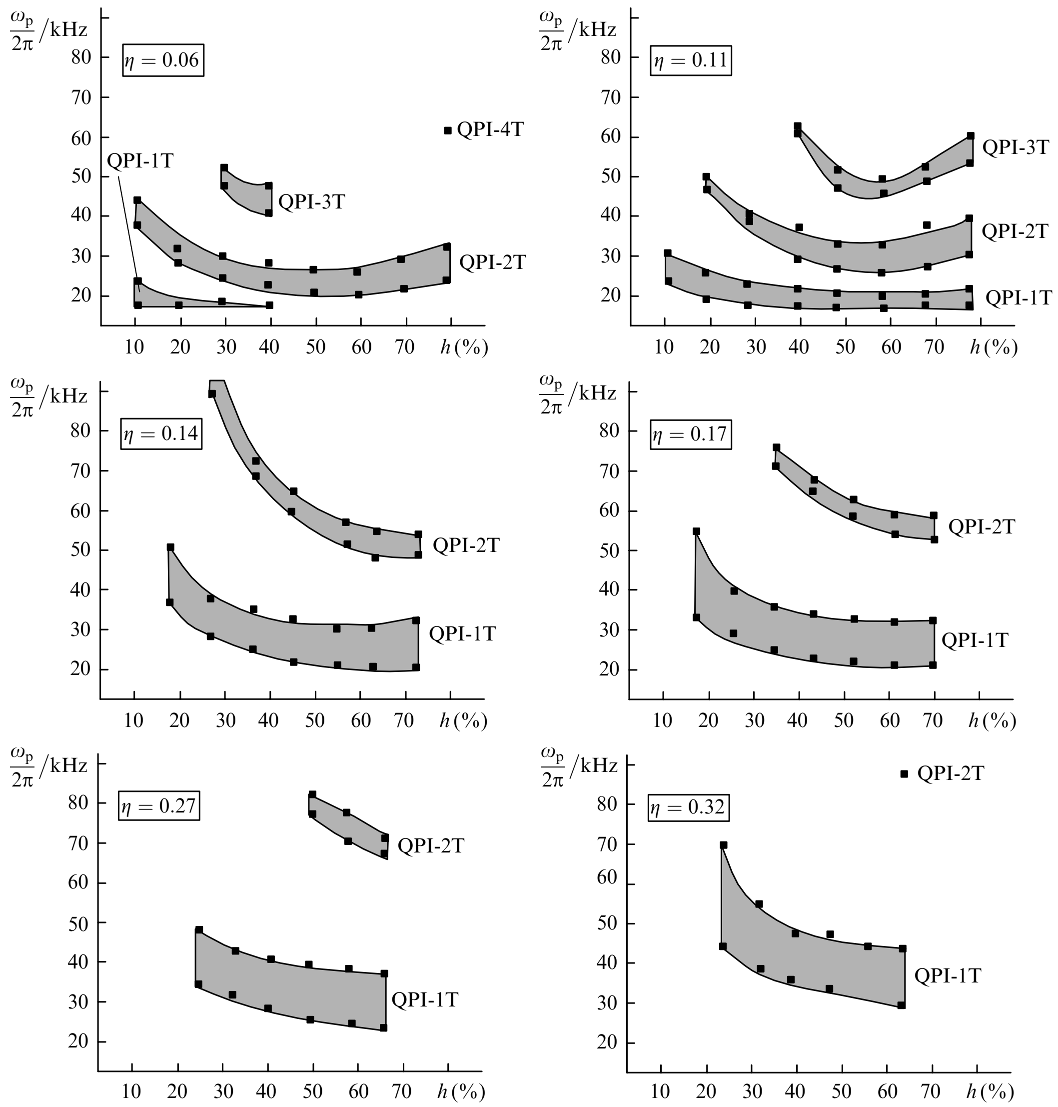

Figure 1. Boundaries of the regions of existence of quasi-periodic and chaotic lasing regimes in the $(\omega_p/2\pi, h)$ plane for different excesses η over the lasing threshold.

repetition rate of $\omega_p/4\pi$ appeared, etc. (according to the classification proposed in [13], the QPI-1T, QPI-2T, QPI-3T, and QPI-4T lasing regimes appeared in the laser).

Figure 1 shows the boundaries of the regions of existence of quasi-periodic and chaotic lasing regimes in the $(\omega_p/2\pi, h)$ plane for different excesses of the pump over the threshold η. The region of existence of the quasi-sinusoidal lasing regime located near the h axis is not shown. One can see that there exist four windows in the range of control parameters studied (3 kHz $\leqslant \omega_p/2\pi \leqslant$ 90 kHz, $0 \leqslant h \leqslant 100$ %, $0.05 \leqslant \eta \leqslant 0.35$) where the QPI-1T, QPI-2T, QPI-3T, and QPI-4T lasing regimes take place.

As the value of η increases, the windows in which quasi-periodic lasing regimes shift to the regions of much higher modulation frequencies $\omega_p/2\pi$. For example, while for $\eta = 0.11$ and $h = 40$ %, the QPI-2T regime can appear at modulations frequencies lying in the range 35–40 kHz, for $\eta = 0.17$ and the same modulation depth, this regime can appear only at modulation frequencies 70–75 kHz. The widths of the regions of existence of quasi-periodic lasing regimes in the $(\omega_p/2\pi, h)$ plane, as follows from experiments, do not exceed 20 kHz, the QPI-1T and QPI-4T regimes having the broadest and narrowest regions of existence, respectively. It follows from the results obtained that the distance between the windows of existence of quasi-periodic regimes in the $(\omega_p/2\pi, h)$ plane increases with the excess of the lasing threshold.

The typical oscillograms of the radiation intensity of counterpropagating waves and the photomixing signal in the QPI-2T lasing regime for $\omega_p/2\pi = 59$ kHz, $\eta = 0.06$, and $h = 30$ % are presented in Fig. 2. Oscillograms of counterpropagating waves and the photomixing signal for other quasi-periodic regimes are similar. Note that the photomixing signal I_{mix} of counterpropagating waves provides information on their phase relations. Analysis of the oscillograms of photomixing signals obtained in the QPI-1T, QPI-2T, and QPI-3T regimes shows that the phase difference of counterpropagating waves changes in the interval between adjacent pulses in all quasi-periodic lasing regimes. Note that the possibility of abrupt changes in optical phases by π in the QPI-1T lasing regime was pointed out earlier in [12, 13].

The results presented above show that in the region of modulation frequencies studied in the paper, the average frequencies of windows, in which quasi-periodic QPI-1T and QPI-2T regimes exist, almost linearly depend on the excess

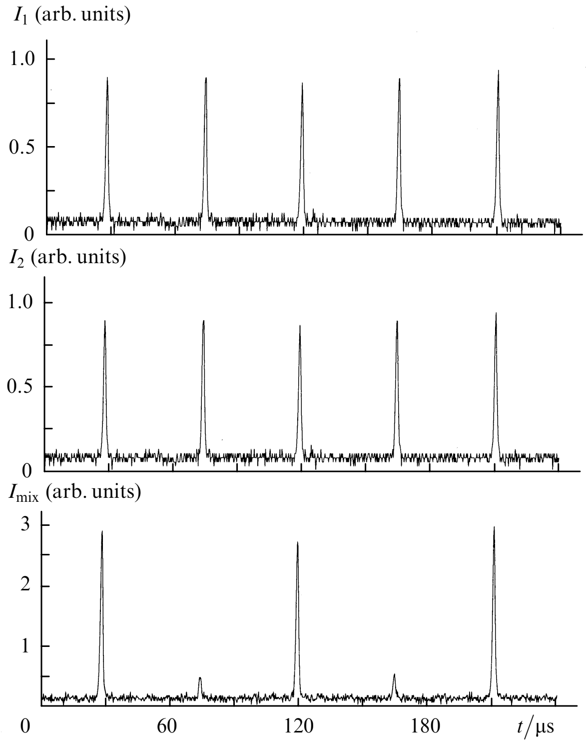

Figure 2. Oscillograms of the radiation intensity of counterpropagating waves and photomixing signal in the quasi-periodic lasing regime for $\omega_p/2\pi = 45$ kHz, $\eta = 0.11$, and $h = 25\,\%$.

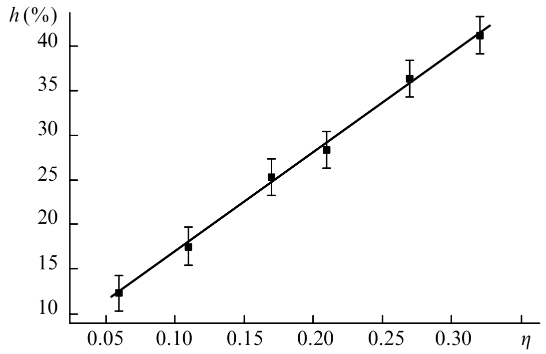

Figure 3. Pump modulation depth required for the appearance of the QPI-2T regime as a function of η.

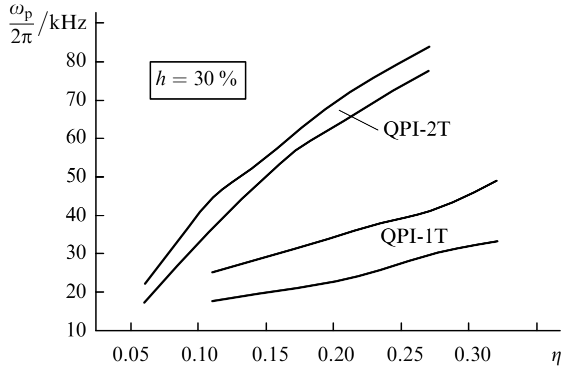

Figure 4. Mutual location of the regions of existence of the QPI-1T and QPI-2T lasing regimes in the $(\omega_p/2\pi,\ \eta)$ plane for $h = 30\,\%$.

of the lasing threshold. Figure 3 presents the pump modulation depth required for the appearance of the QPI-2T regime as a function of η. The mutual location of the regions of existence of the QPI-1T and QPI-2T lasing regimes in the $(\omega_p/2\pi,\ \eta)$ plane for $h = 30\,\%$ is shown in Fig. 4.

4. Conclusions

We have studied in detail transient oscillation regimes of a highly stable monolithic ring chip Nd : YAG laser pumped by harmonically modulated radiation. The appearance of windows in the region of dynamic chaos in which quasi-periodic regimes QPI-1T and QPI-4T are observed with pulse repetition rates different by four times was demonstrated. The regions of existence of these quasi-periodic regimes are determined depending on the control parameters such as the excess over the lasing threshold, the frequency and depth of pump modulation. The evolution of the regions of existence and stability of quasi-periodic and chaotic lasing regimes caused by variations in the pump power was investigated. A scenario of the passage from the self-modulation regime of the first kind to dynamic chaos was considered.

It is shown that the behaviour of the regions of existence of the lasing regimes strongly depends on the value of control parameters. The peculiarities of the behaviour of a self-oscillation system (in particular, a ring laser) can be useful not only for laser physics but also for other fields of nonlinear dynamics.

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