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Frequency locking of self-modulated oscillations and hysteresis of a nonautonomous two-directional ring solid-state laser

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***Abstract*. The effect of the pump modulation on the lasing dynamics of a two-directional ring solid-state laser operating in the self-modulated regime is studied experimentally. The frequency locking was observed when the pump modulation frequency approached the self-modulation frequency. The dependence of the locking band on the laser characteristics and parameters of an external signal is studied. The frequency locking exhibits hysteresis.**

Keywords: *ring laser, frequency locking, self-modulation regime.*

1. Introduction

One of the interesting lasing regimes of two-directional ring lasers is the self-modulation regime of the first kind, which is characterised by the out-of-phase harmonic modulation of the intensities of counterpropagating waves. The self-modulation frequency ω_m in an autonomous ring laser is determined in the first approximation by the effective coupling coefficient m of counterpropagating waves via backward scattering and by the frequency nonreciprocity Ω of the laser cavity:

$$\omega_\mathrm{m} = \left(m^2 + \Omega^2\right)^{1/2},$$

where m is determined by the expression

$$m = m_1 m_2 \cos(\theta_1 - \theta_2) + \frac{(1+\delta) m_1^2 m_2^2 \sin^2(\theta_1 - \theta_2)}{m_1^2 + m_2^2 + 2 m_1 m_2 \cos(\theta_1 - \theta_2) - \delta m_1 m_2 \sin(\theta_1 - \theta_2)}.$$

Here, m_1 and m_2 are the moduli of complex coupling coefficients for counterpropagating waves; θ_1 and θ_2 are the phases of coupling coefficients [1]; and δ is the detuning of the lasing frequency from the centre of the gain line.

A solid-state ring laser operating in the self-modulation regime represents a nonlinear oscillating system, which is very sensitive to various external actions. It was found recently that a permanent magnetic field applied to an active medium caused a phase shift between the self-modulated oscillations of counterpropagating waves [2].

The periodic modulation of the parameters of a solid-state laser can especially strongly affect its self-modulation regime. Experiments show that even weak periodic perturbations of the parameters (cavity losses or pump intensity) of such a nonautonomous laser can drastically affect its lasing dynamics [3].

The self-modulation regime of the first kind in solid-state lasers attracts recent attention of researchers studying the features of the development of dynamic chaos in such lasers. In particular, it was shown in paper [4] that the modulation of the pump of a solid-state ring laser can result, under certain conditions, in the passage from the self-modulation regime to the dynamic chaos. A similar effect takes place upon excitation of parametric resonances in a ring laser [5].

In this paper, we study some new properties of the nonlinear dynamics of a ring solid-state laser operating in the self-modulation regime of the first kind upon periodic modulation of the pump power, namely, a change in the self-modulation frequency, as well as the frequency locking and hysteresis.

2. Experimental

The principal scheme of the experimental setup is shown in Fig. 1. We studied a diode-pumped 1.06-μm $\mathrm{Nd}^{3+}:\mathrm{YAG}$ monolith ring chip laser (*1*). The perimeter of the laser

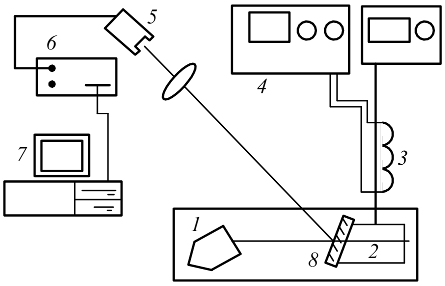

Figure 1. Principal scheme of the experimental setup; (*1*) monolith ring chip laser; (*2*) semiconductor laser diode; (*3*) coil; (*4*) ac voltage generator; (*5*) LFD-2 photodetector; (*6*) ACK-3151 digital oscilloscope; (*7*) PC; (*8*) selective mirror.

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resonator was 2.6 cm, and the nonplanarity angle was 80°. The laser was longitudinally pumped by a laser diode (*2*) with the output power up to 500 mW. The laser design is described in detail in Ref. [6]. The pump radiation was modulated in the frequency range from 50 to 250 kHz. The modulation was performed by means of a coil (*3*) included in a power circuit of the laser diode and connected to an ac voltage generator (*4*). The modulation degree was controlled by varying the voltage amplitude on the coil and could achieve 60 %. Laser radiation was detected with an LFD-2 photodetector (*5*), then the signal was fed to an ACK-3151 digital oscilloscope (*6*), and processed with a PC (*7*).

In the absence of external perturbations, the laser operated in the self-modulation regime. The self-modulation frequency $\omega_m/2\pi$ was 230 kHz. The intracavity losses were determined experimentally from the Q factor of the ring cavity, which can be readily found by measuring the relaxation frequency

$$\omega_r = \left(\frac{\omega\eta}{QT_1}\right)^{1/2},$$

where ω is the lasing frequency; η is the excess of the pump power over the threshold; and T_1 is the relaxation time of a metastable level. Under our experimental conditions, $\eta = 0.21$, $\omega_r/2\pi = 70$ kHz, $\omega/Q = 7 \times 10^6$ s^{-1}.

3. Experimental results

We studied the time and spectral dependences of output emission of a two-directional ring laser on the frequency ω_{ext} and degree of modulation h of its pumping.

In the absence of modulation ($h = 0$), a typical self-modulated lasing was observed with the emission spectrum consisting of one line with a frequency corresponding to the self-modulation frequency ω_m. When the pump radiation was modulated at the frequency ω_{ext} ($h = 10\,\% - 60\,\%$) located far away from the self-modulation frequency, a second line with frequency ω_{ext} appeared in the emission spectrum. In this case, the modulation of intensities of counterpropagating waves was no longer sinusoidal.

When the modulation frequency ω_{ext} was close enough to the frequency ω_m, the self-modulation frequency was locked by an external signal (the self-modulation frequency in the frequency locking region proved to be equal to the external perturbation frequency ω_{ext}, and no distortions of the self-modulation signal, i.e., no deviations of its shape from a sinusoidal one, were observed. The width $\Delta\omega_{max}$ of the frequency locking region depended on the excess η of the pump energy over the threshold and the modulation degree h.

We found that the behaviour of the laser depended on the direction of frequency tuning ω_{ext} ($\Delta\omega = \omega_{ext} - \omega_m$). The self-modulation frequency exhibited a jump upon frequency locking only when the conditions $\omega_m - |\Delta\omega|_{max} < \omega_{ext} < \omega_m$ were satisfied, and the frequency jump was absent when $\omega_{ext} > \omega_m$.

This is illustrated in Figs 2–5. The emission spectra of the laser in the absence and in the presence of locking of the self-modulation frequency by an external signal are presented in Fig. 2. One can clearly see the shift (jump) of the self-modulation frequency caused by its locking. Also, the dependence of $|\omega_m - \omega_{ext}|_{max}/2\pi$ on the direction of frequency tuning is observed, which indicated to the hysteresis nature of this effect.

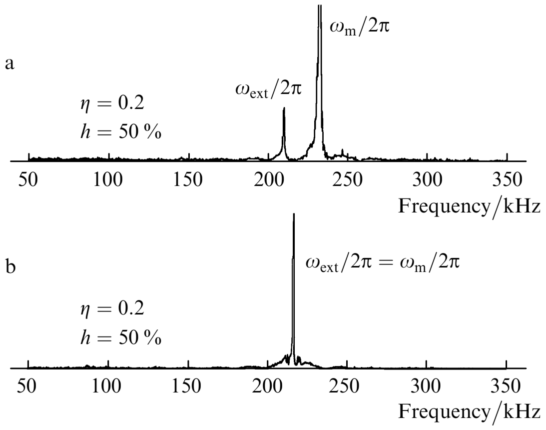

Figure 2. Emission spectra of the laser in the absence (a) and presence (b) of locking of the self-modulation frequency by an external signal for $\eta = 0.2$ and $h = 50\,\%$.

Fig. 3 shows the dependences of the maximum width of the frequency locking on the degree h of pump modulation for frequency tuning in two opposite directions. One can see that the width of the frequency-locking region can achieve 20 kHz. Figs 4 and 5 show the dependences of the maximum width of the frequency-locking region on the degree h of pump modulation and the excess η of the pump power over the threshold for two opposite directions of the frequency tuning. A comparison of the curves in Figs 4 and 5 also shows the hysteresis of the dependence $|\omega_m - \omega_{ext}|_{max}/2\pi$.

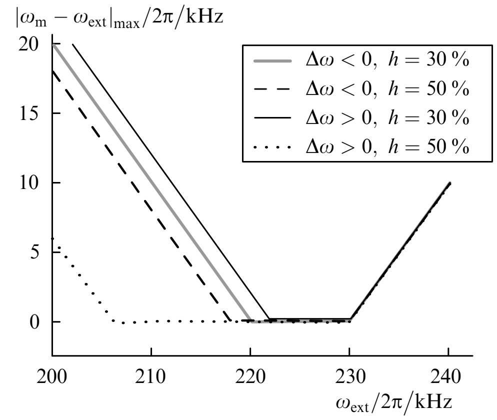

Figure 3. Dependences of the width of the frequency-locking region on h and the initial position $\Delta\omega$ for $\eta = 0.17$.

As the pump modulation frequency approaches the relaxation frequency, the self-modulation regime, as expected, passes to the dynamic chaos. The width of the frequency-locking region (the frequency region $\omega_r - \omega_{ext}$ where the dynamic chaos existed) was of about 10 kHz in this case.

4. Conclusions

We have shown experimentally that upon periodic modulation of the pump radiation of a solid-state ring laser operating in the self-modulation regime, the width of the

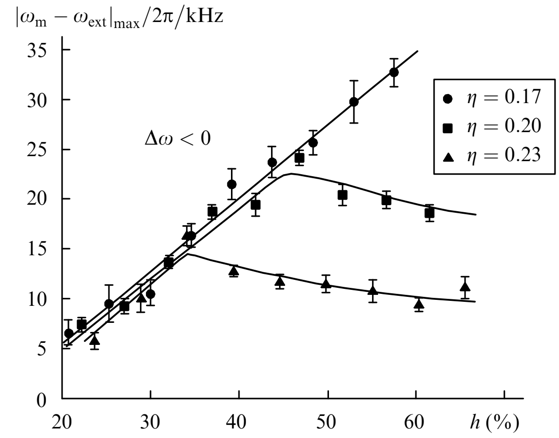

Figure 4. Dependences of the width of the frequency-locking region on h for the initial position $\Delta\omega < 0$.

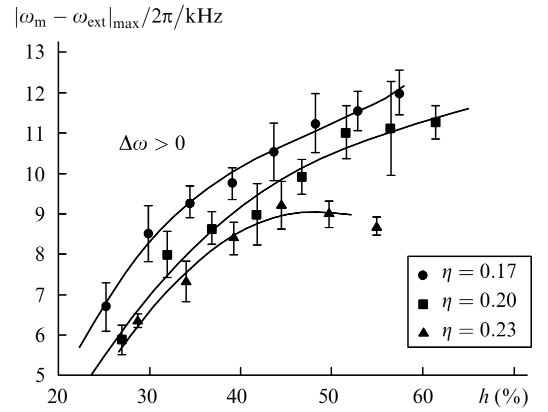

Figure 5. Dependences of the width of the frequency-locking region on h and η for the initial position $\Delta\omega > 0$.

region of locking of the self-modulation frequency by the external frequency (i.e., the region where the self-modulation frequency proves to be equal to the external perturbation frequency) can achieve several tens of kilohertz. In this case, the frequency locking occurs only when the self-modulation frequency exceeds the external frequency.

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