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CONTROL OF LASER RADIATION PARAMETERS

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Control of generation regimes of ring chip laser under the action of the stationary magnetic field

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Abstract. **We consider realisation of different generation regimes in an autonomous ring chip laser, which is a rather complicated problem. We offer and demonstrate a simple and effective method for controlling the radiation dynamics of a ring Nd : YAG chip laser when it is subjected to a stationary magnetic field producing both frequency and substantial amplitude nonreciprocities. The amplitude and frequency nonreciprocities of a ring cavity, arising under the action of this magnetic field, change when the magnet is moved with respect to the active element of the chip laser. Some self-modulation and stationary generation regimes as well as the regime of beatings and dynamic chaos regime are experimentally realised. Temporal and spectral characteristics of radiation are studied and conditions for the appearance of the generation regime are found.**

Keywords: *solid-state ring laser, self-modulation generation regime, regime of beatings, dynamic chaos, amplitude and frequency nonreciprocities of ring cavity.*

1. Introduction

Solid-state ring lasers (SRLs) with a homogeneous gain are complicated dynamic systems, capable of operating in various generation regimes differing in temporal, spectral, and polarisation characteristics of radiation. Nonlinear dynamics of SRL radiation was studied in many papers (see, for example, reviews [1 – 5] and references therein). Investigations conducted show that in a nonautonomous SRLs [4] (in particular, in SRLs with a periodic modulation of parameters), the variety of observed generation regimes is substantially wider than in the case of autonomous SRLs [2, 3, 5].

Monolithic (single-block) SRLs (ring chip lasers) are of particular scientific and practical interest. The specific features of monolithic lasers are high temporal, frequency, and polarisation stability of radiation, weak sensitivity to external actions, and high efficiency. In practical applications those suggest a possibility to efficiently control the generation regime. In SRLs comprising discrete elements the regime of generation is usually changed (switched) by placing control elements inside the cavity. From this point of view, ring chip lasers have a drawback which limits their practical use, because intracavity control elements cannot be employment in such lasers.

This problem can be solved by applying an external stationary magnetic field, which produces the optical nonreciprocity of a ring cavity [3, 6 – 9]. Theoretical and experimental investigations conducted earlier show that the amplitude and frequency nonreciprocities of the cavity of a ring laser can be successfully used as the control parameters capable of varying temporal and spectral characteristics of the output radiation of such lasers. In particular, an external magnetic field applied to the active element of a ring chip laser allows one to realise the regime of unidirectional generation (the travelling wave regime) [8, 9]. It was also shown that the external magnetic field may result in the frequency nonreciprocity when the laser operates in the self-modulation regime of the first kind [7]. Note that in the preceding experimental investigations the dynamics of bidirectional generation was controlled by an external magnetic field in the ring chip lasers possessing the frequency nonreciprocity whereas the amplitude nonreciprocity was either absent or negligible [7].

Interesting are studies of the possible control of emission dynamics in a more general case: at an arbitrary relation between the frequency and amplitude nonreciprocities. In the present work we perform experimental investigations of the dynamics of a ring Nd:YAG chip laser with the external static magnetic field which produces both the frequency and amplitude nonreciptocities. Our experiments have shown that the generation regime of the SRL can be efficiently controlled by applying an external stationary magnetic field to the ring chip laser.

2. Experimental setup

The chip laser under study was a single-block in the form of the prism with one spherical (the radius of curvature is 50 mm) face and three plane highly reflecting faces. The geometrical perimeter of the cavity was 2.8 cm and the angle of cavity nonflatness was 80°. On the upper surface of the prism (Fig. 1a), the magnet in the form of the rectangular parallelepiped (brick) of dimension 12 × 8 × 5 mm was placed oriented (the longer side) along the axis of symmetry X of the prism. In the experiments, the centre of the brick (point C) moved along the X axis (by means of a micrometer adjustment unit) in the limits $0 \leqslant X_C \leqslant 1$ mm (Fig. 1b).

The spatial distribution of the inhomogeneous magnetic field produced by the magnet was symmetric about the plane of symmetry of the single-block. The amplitude and frequency nonreciprocities of the ring cavity arising under the action of the magnetic field varied in a sufficiently wide range under magnet displacements.

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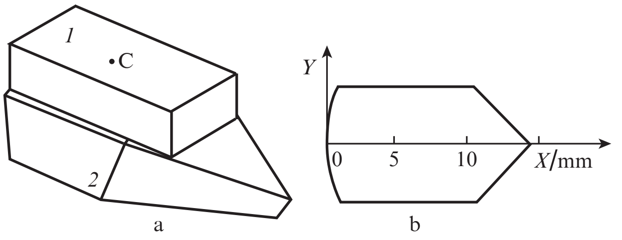

Figure 1. (a) Relative positions of (*1*) a magnet and (*2*) an active element of a chip laser and (b) schematic diagram illustrating the magnet position (point C) on the *X* axis and interval of magnet displacements.

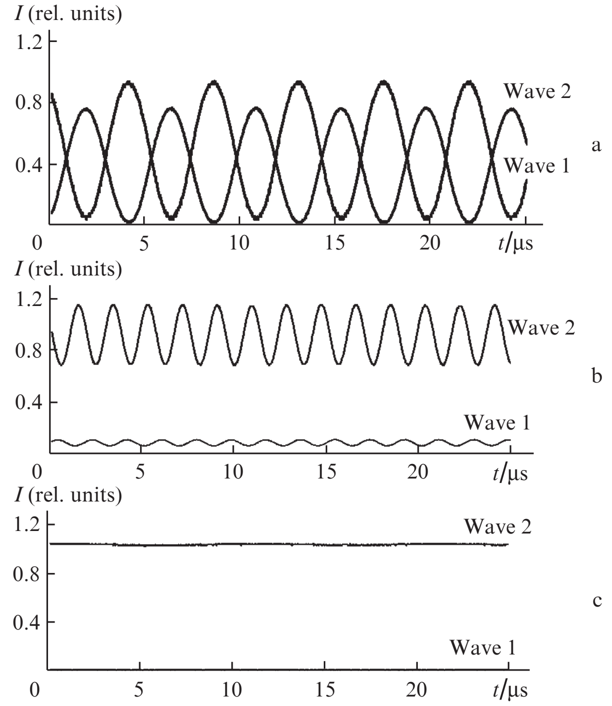

Figure 2. Oscillograms of the intensities of counterpropagating waves 1 and 2 in the self-modulation regime of the first kind (a) without external magnetic field and (b) with the magnet centre positioned at point X_C = 13 mm; (c) oscillogram of the intensities of counterpropagating waves in the stationary regime of unidirectional generation at the magnet centre positioned at point X_C = 7.5 mm.

Note that the optical nonreciprocity arising under the magnetic field applied to the single-block of a chip laser can be exactly calculated only in the case of a uniform field. Otherwise, such a calculation is a hard task. The nonreciprocity of a ring chip laser can be measured for the laser operating in the self-modulation regime of the first kind; however, this regime occurs only within a limited range of magnet positions. Thus, in what follows we will specify the position of magnet centre on the *X* axis (Fig. 1b).

In the course of investigations we have simultaneously recorded temporal and spectral characteristics of the radiation intensities of counterpropagating waves in a ring chip laser versus the position of the magnet. The radiation characteristics were recorded by a Tektronix TDS 2014 digital oscilloscope.

3. Results of experiments

Without the external magnetic field the laser under study operated in the self-modulation regime of the first kind. The study was conducted at the constant excess of pumping over a threshold value $\eta = 0.08$. The self-modulation frequency in this case was f_m = 225 kHz and the base relaxation frequency was f_r = 89.5 kHz. The characteristic oscillograms of the intensities of counterpropagating waves are presented in Fig. 2a. One can see that the average intensities of the counterpropagating waves I_1 and I_2 are not equal. As was mentioned in [10], in the chip laser under investigation the ratio of the average intensities for the oncoming waves I_1/I_2 can be controlled by changing the temperature of the single-block. In the experimental conditions of the present work we have chosen the single-block temperature that provided the ratio $I_2/I_1 = 1.2$.

As the magnet approaches the laser single block, the self-modulation regime of the first kind is preserved if the magnet centre position is within the range 7.5 mm $\leqslant X_C \leqslant$ 13 mm. In this range, the characteristics of the self-modulaion oscillations depended on the magnet position. The amplitude and frequency nonreciprocities arising in a chip laser under the action of the magnetic field lead to an increase in the frequency of self-modulation oscillations f_m. With an increase in f_m, the initially weaker wave (wave 2) was suppressed, whereas the intensity of the oncoming wave (wave 1) increased. In this case, the intensity modulation depth noticeably reduced. Fig. 2b shows the intensity oscillograms of the counterpropagating waves for the magnet centre position corresponding to X_C =13 mm. The self-modulation frequency in this case was f_m = 550 kHz.

The investigations conducted show that there are certain ranges of magnet centre positions X_C, in which bifurcations are observed and the chip laser generates in other regimes. In addition to the self-modulation regime of first kind, other self-modulation regimes were observed with substantially unequal intensities of the counterpropagating waves.

3.1. Regimes of unidirectional generation

In reducing the self-modulation depth of counterpropagating waves down to zero (X_C = 7.5 mm), the self-modulation regime vanishes and a stationary regime of unidirectional generation arises (see Fig. 2c). The ratio of the intensities I_1/I_2 in this case is equal to 0.02 and still reduces at magnet displacements. At a magnet position in the range X_C < 6.5 mm, the stationary unidirectional regime becomes unstable. The instability leads to self-excitation of relaxation oscillations of the radiation intensity. In the experiments, this resulted in the unidirectional generation with self-modulation oscillations at a relaxation frequency not observed experimentally yet. Intensity oscillograms of counterpropagating waves in the self-modulation regime of unidirectional generation are shown in Fig. 3. The self-oscillations with a small modulation depth are sinusoidal and have the frequency f_r = 89.5 kHz. At further magnet movement along the *X* axis the depth of modulation at the relaxation frequency increases to almost 100% (see Fig. 3b).

3.2. Regime of dynamic chaos

The study conducted in the present work demonstrated the regime of dynamic chaos arising in an autonomous SRL. Previously, the regime of chaos in an autonomous SRL was only observed under an additional feedback realised for coun-

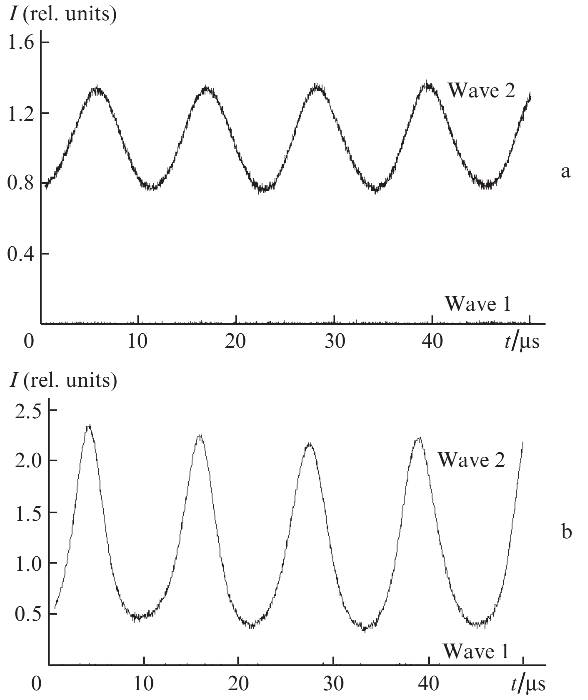

Figure 3. Oscillograms of the intensities of counterpropagating waves 1 and 2 in the periodical self-modulation regime of unidirectional generation at the magnet centre positioned at point X_C = (a) 6.45 and (b) 6.53 mm.

terpropagating waves by external mirrors [11]. The regime of dynamic chaos in the laser under study arises from the self-modulation regime of unidirectional generation in the range 5.4 mm $< X_C <$ 6.5 mm. The characteristic intensity oscillograms for counterpropagating waves in the regime of dynamic chaos are shown in Fig. 4. One can see that the average intensity values of the waves substantially differ (the average intensity of wave 1 is much lower than that of wave 2). Hence, in the regime of dynamic chaos the generation is close to unidirectional. The intensity spectrum of the strong wave 2 for this regime is shown in Fig. 5. One can see that the spectrum of the stronger wave has the region with the continuous frequency spectrum, which is characteristic for dynamic chaos.

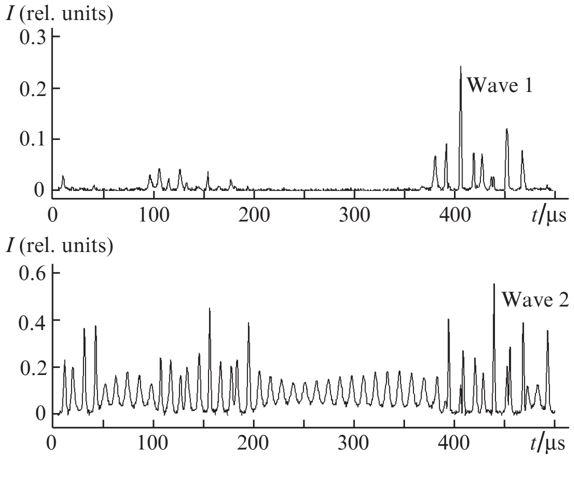

Figure 4. Oscillograms of the intensities of counterpropagating waves 1 and 2 in the regime of dynamic chaos. The magnet centre is at point X_C = 6 mm.

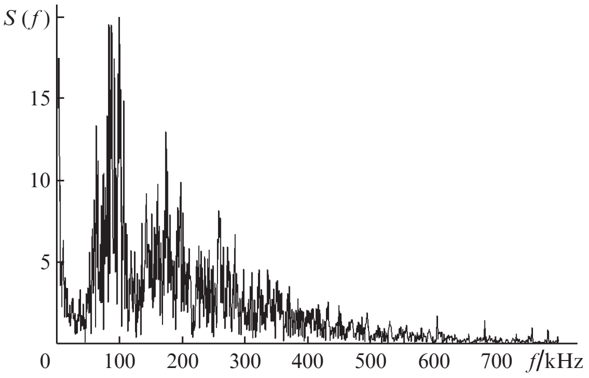

Figure 5. Spectrum of intensity $S(f)$ of the strong wave 2 in the regime of dynamic chaos. The magnet centre is at point X_C = 6 mm.

3.3. In-phase self-modulation regime of generation

In the range 5 mm $< X_C <$ 5.5 mm the regime of dynamic chaos switches to the in-phase self-modulation generation regime. In this regime, for the first time observed in [12], unlike the self-modulation regime of the first kind, the in-phase intensity modulation of counterpropagating waves occurs instead of the opposite phase intensity modulation. Figure 6 shows the intensity oscillograms of counterpropagating waves at X_C = 5.5 mm where the in-phase pulsed modulation of the intensities of counterpropagating waves is observed at the relaxation frequency. The average intensities of counterpropagating waves noticeably differ in this regime.

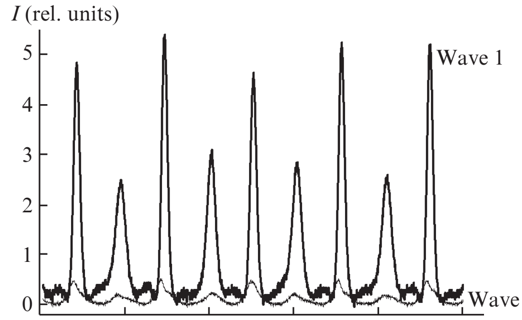

Figure 6. Oscillograms of the intensities of counterpropagating waves 1 and 2 in the regime of in-phase self-modulation of the intensities of counterpropagating waves at the magnet centre positioned at point X_C = 5.5 mm.

In the range 3 mm $< X_C <$ 5 mm, the regime of quasi-periodic self-modulation oscillations arises with a opposite-phase low-frequency envelope, which was thoroughly studied in [13].

3.4. Regime of beatings with equal average intensities of counterpropagating waves

In [14] it was for the first time reported (see also review [1]) that at the large frequency nonreciprocity that considerably exceeds the frequency of the self-modulation oscillations arising without the nonreciprocity, a transfer may occur from the regime of unidirectional generation to that of counterpropagating wave beatings with equal average intensities. The investigations of the present work show that such a transition is also observed in a ring chip laser. At $X_C = 1.5$ mm, the average intensities of counterpropagating waves become equal and opposite phase modulation of the intensity occurs at the beating frequency $f_b = 1524$ kHz, which is determined by the frequency unreciprocity. Oscillograms of the intensities of counterpropagating waves in the beating regime are given in Fig. 7.

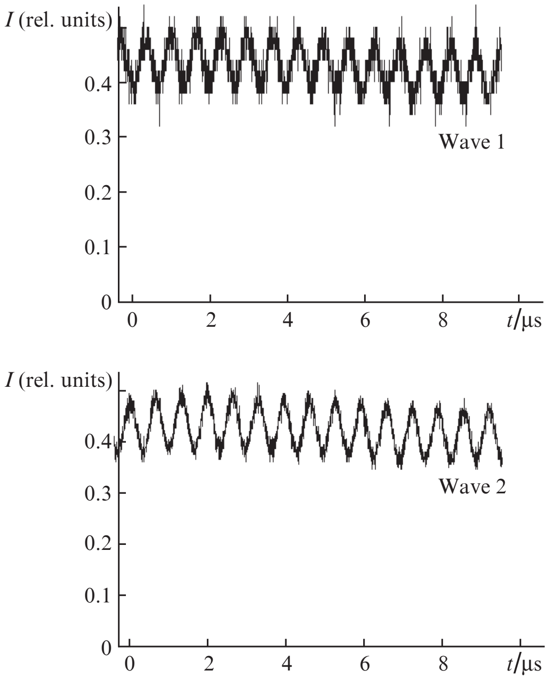

Figure 7. Oscillograms of the intensities of counterpropagating waves 1 and 2 in the regime of beatings with equal average values of the intensities at the magnet centre positioned at point $X_C = 1.5$ mm.

If the magnet is still moved to the range $X_C < 1.5$ mm the laser again transfers to a stationary regime of unidirectional generation; however, the direction of the stronger wave changes to opposite (wave 1 becomes strong).

4. Conclusions

Thus, a simple and efficient method is found for controlling the radiation dynamics of an autonomous ring Nd:YAG chip laser under an action of the stationary external magnetic field, which produces both the frequency and noticeable amplitude nonreciprocity. The experimental investigations conducted show that the method suggested allows one to realise and control a set of generation regimes for autonomous ring chip laser. A number of self-modulation and stationary generation regimes and the regimes of beatings and dynamic chaos have been realised experimentally.

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