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Quasi-periodic regime of self-modulation oscillations with a periodic low-frequency envelope in a ring chip laser

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***Abstract*. The dynamics of a ring chip Nd:YAG laser radiation in an external static magnetic field inducing an optical nonreciprocity of the resonator is studied experimentally. The amplitude and frequency nonreciprocities of the ring cavity induced by this magnetic field varied with moving the magnet with respect to the active element of the chip laser. A previously unknown quasi-periodic self-modulation lasing regime in which the self-modulation intensity oscillations of counterpropagating waves have an antiphase low-frequency envelope is found. The temporal and spectral characteristics of radiation are studied and the conditions of the appearance of this lasing regime are determined.**

Keywords: *solid-state ring laser, self-modulation lasing regime, amplitude and frequency nonreciprocities of ring resonators.*

1. Introduction

Interest in the dynamics of solid-state ring lasers is explained by their potential applications in both fundamental physics (search for gravitational waves, verification of the fundamental concepts of quantum electrodynamics and theory of relativity, fundamental quantum metrology, etc.) and laser engineering (Doppler measuring systems, optical communication, laser gyroscopes, etc.). Investigations in the field of nonlinear dynamics of ring lasers also make a considerable contribution to understanding the general behaviour of nonlinear dynamic systems of various natures (in radio engineering, optics, biology, chemistry, mechanics, etc.).

Solid-state ring lasers with a homogeneously broadened gain line are complex dynamic systems in which the nonlinear coupling of counterpropagating waves on a spatial inverse-population grating induced by these waves, as well as their linear coupling due to backscattering, can lead to the appearance of lasing regimes differing in temporal, spectral, and polarisation characteristics of radiation. The nonlinear dynamics of radiation of solid-state ring lasers was studied in numerous works (see, for example, reviews [1 – 4] and references therein). The main ring laser parameters that determine the stability of stationary lasing regimes include the backscattering coupling coefficients of counterpropagating waves $m_{1,2}$. At $m_{1,2}$ typical for monolithic ring lasers (ring chip lasers), the stationary unidirectional lasing is unstable. This results in the appearance of the self-modulation regime of the first kind – a periodic regime with an antiphase sinusoidal intensity modulation of counterpropagating waves.

The self-modulation regime of the first kind exists and is stable in a wide range of ring chip laser parameters, except for the regions at which the frequency of self-modulation oscillations is close to the doubled main relaxation frequency. In these regions, due to parametric interactions between the self-modulation and relaxation oscillations, the self-modulation regime of the first kind is unstable, and lasing occurs in other self-modulation regimes, namely, in a regime with a doubled modulation period [5, 6] and in a quasi-periodic self-modulation regime [7].

In principle, the sufficiently weak coupling of counterpropagating waves via backscattering and the existence of a rather strong phase-amplitude coupling in solid-state ring lasers can cause a self-modulation regime of the second kind [8 – 10], which is characterised by a quasi-periodic low-frequency switching of the lasing direction. However, this regime usually does not occur in ring chip lasers [4] because the backscattering coupling coefficients of counterpropagating waves are too high [due to a small (of several centimetres) perimeter of the monoblock cavity].

The creation of an additional feedback between counterpropagating waves by using external mirrors allowed us to obtain other self-modulation regimes: a periodic in-phase self-modulation regime [11] and a dynamic chaos regime [5].

Of great interest for practical applications of monolithic chip lasers is the possibility to effectively control lasing regimes. In solid-state ring lasers consisting of discrete elements, lasing regimes are usually changed (switched) using intracavity controlling elements. From this viewpoint, the drawback restricting the practical use of ring chip lasers is the impossibility of using intracavity controlling units.

This problem can be solved by using an external static magnetic field to create optical nonreciprocity of the ring cavity [3, 12 – 15]. Previous theoretical and experimental investigations showed that the amplitude and frequency nonreciprocities of a ring laser cavity can be successfully used as controlling parameters for changing the temporal and spectral characteristics of the output radiation of these lasers. In particular, application of an external field to the active element of a ring chip laser allows one to achieve

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stationary unidirectional lasing (travelling wave regime) [14, 15]. It was also shown that an external magnetic field makes it possible to create a frequency nonreciprocity in lasers operating in the self-modulation regimes of the first kind [13]. Note that, in the previous experiments, the bidirectional lasing dynamics was controlled using an external magnetic field when the frequency nonreciprocity in the ring chip lasers was significant and the amplitude nonreciprocity was either absent or rather small [13].

Of undoubted interest are studies of the possibility of controlling the radiation dynamics in the more general case of a arbitrary ratio between the frequency and amplitude nonreciprocities. We experimentally studied the dynamics of a Nd : YAG ring chip laser in an external static magnetic field, which induced both a frequency and a considerable amplitude nonreciprocities.

The aim of the present work is to study the temporal and spectral characteristics of radiation in a new observed regime of self-modulation intensity oscillations of counterpropagating waves with an antiphase low-frequency envelope.

2. Experimental setup

The studied chip laser was a monoblock in the form of a prism with one spherical face (radius of curvature 50 mm) and three plane total-internal-reflection faces. The geometric perimeter of the resonator was 2.8 cm, and the resonator nonplanarity angle was 80°. Onto the upper face of the prism (Fig. 1a), we placed a magnet in the form of a rectangular parallelepiped with dimensions $12 \times 8 \times 5$ mm so that its longest edge was oriented along the symmetry axis x of the prism and we can move the magnet in this direction using a micropositioner (Fig. 1b). The spatial distribution of the applied inhomogeneous magnetic field was symmetric with respect to the symmetry plane of the monoblock. With moving the magnet, the amplitude and frequency nonreciprocities of the ring cavity induced by this magnetic field varied within a rather wide range.

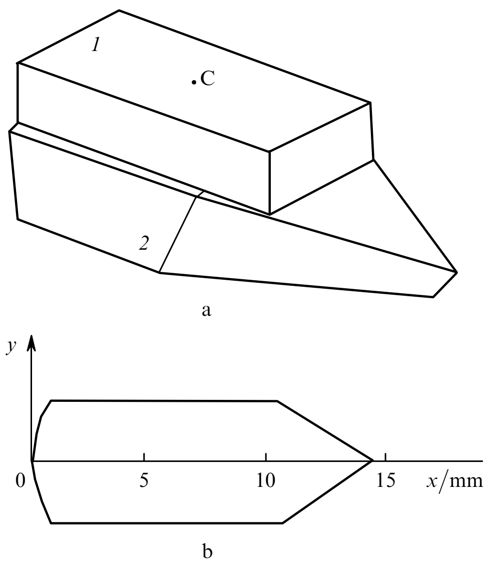

Figure 1. Relative positions of the magnet (*1*) and active element (*2*) of a chip laser (a) and scheme demonstrating the range of displacement ($0 \leqslant x \leqslant 13$ mm) of the magnet centre (point C) along the x axis (b).

It should be noted that the optical nonreciprocity induced by a magnetic field applied to a chip laser monoblock can be precisely calculated only in the case of a homogeneous field. In the case of an inhomogeneous field, these calculations are very difficult. The nonreciprocity in a ring chip laser can be measured when the laser operates in the self-modulation regime of the first kind, but this regime occurs only in a limited range of magnet positions. Below, we will indicate the position of the magnet centre (point C) on the x axis (see Fig. 1b). Using a Tektronix TDS 2014 digital oscilloscope, we simultaneously recorded the temporal and spectral characteristics of the intensities of counterpropagating waves in the ring chip laser depending on the magnet position.

3. Experimental results

In the absence of an external magnetic field, our laser operated in the self-modulation regime of the first kind. The experiments were performed at a fixed excess of the pump power over the lasing threshold, $\eta = 0.08$. The self-modulation frequency $\omega_{\rm m}/2\pi$ was 225 kHz, and the main relaxation frequency $\omega_{\rm r}/2\pi$ was 89.5 kHz.

Our investigations showed that, in the presence of an external magnetic field, there exist rather wide regions of magnet positions on the x axis in which bifurcations appear and lasing switches to other regimes. In our experiment, the magnet centre was moved within the range $0 \leqslant x \leqslant 13$ mm. When the magnet centre position varied within the range $5 \leqslant x \leqslant 13$ mm, we observed unidirectional lasing regimes. One of these regimes was the stationary unidirectional regime, in which the strong wave intensity is constant in time. In addition, self-modulation regimes with significantly different intensities of counterpropagating waves also appeared. In these regimes, the in-phase intensity modulation of the strong and weak waves took place; the results of investigation of these regimes will be published later. Note that the fact of switching of the ring chip laser from the self-modulation regime of the first kind to regimes with considerably different intensities of counterpropagating waves is evidence of the existence of a significant amplitude nonreciprocity induced in the cavity by the magnetic field.

When the magnet centre is moved to the region $3 \leqslant x \leqslant 5$ mm, the in-phase self-modulation regimes with considerably different intensities of counterpropagating waves change to a bidirectional lasing regime with periodic antiphase self-modulation of the intensities of counterpropagating waves, which was not observed previously and is the object of this study.

Typical oscillograms of the intensities of counterpropagating waves in this regime are shown in Fig. 2, which demonstrates complex-shape quasi-periodic antiphase oscillations of these intensities. During a larger part of the low-frequency self-modulation period T ($T \approx 81$ μs), the intensity of one of the counterpropagating waves (I_1) considerably exceeds the intensity of the other wave (I_2). The strong wave is modulated with the relaxation oscillation frequency $\omega_{\rm r}/2\pi = 89.5$ kHz. In the remaining part of the period, the intensities of the counterpropagating waves are equalised and one observes their antiphase self-modulation with the frequency $\omega_{\rm m}/2\pi = 550$ kHz determined by the coupling of counterpropagating waves and by the frequency nonreciprocity of the cavity.

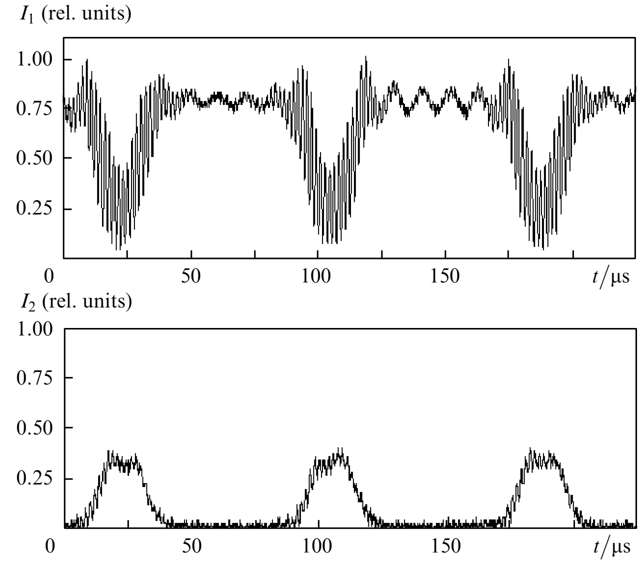

Figure 2. Oscillograms of the intensities of counterpropagating waves $I_{1,2}$ in the self-modulation regime with a periodic antiphase envelope.

The spectra of the intensities of counterpropagating waves (Fig. 3) contain the following components: low-frequency components which are multiple of the pulse repetition rate $f = 1/T = 12.3$ kHz in the envelope; some equidistant (spaced by the same 12.3 kHz) components near the main relaxation frequency; several equidistant components in the vicinity of the doubled relaxation frequency; and, finally, equidistant components in the region of the self-modulation frequency $\omega_m/2\pi = 550$ kHz.

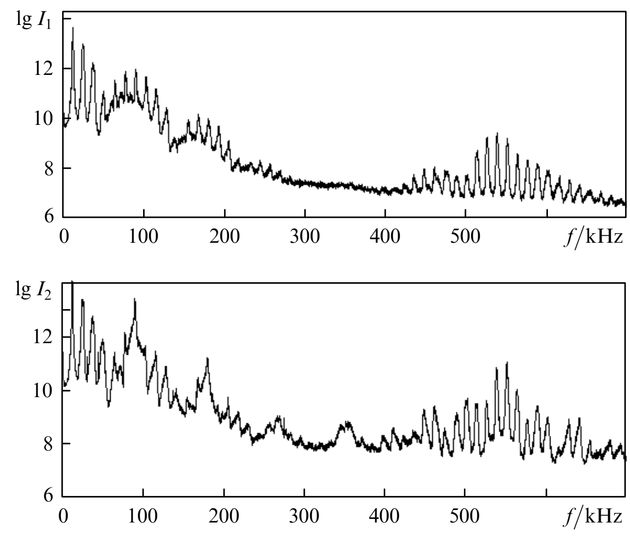

Figure 3. Spectra of the intensities of counterpropagating waves $I_{1,2}$ in the self-modulation regime with a periodic antiphase envelope.

It should be noted that the studied regime occurs in a relatively narrow range of optical nonreciprocities. Since the optical nonreciprocity (both amplitude and frequency) in this regime cannot be measured directly, the width of this region can be estimated only qualitatively by the interval of the magnet centre positions within which this regime occurs ($3 \leqslant x \leqslant 5$ mm). In addition, the frequency nonreciprocity can be qualitatively estimated by the variations in the self-modulation frequency $\omega_m/2\pi$ (the application of the magnetic field changed it from the initial value of 225 kHz to 550 kHz).

When the magnet moves within the range of $3 \leqslant x \leqslant 5$ mm, this regime is retained, but the shape of the self-modulation oscillations of the strong wave intensity changes, namely, the modulation depth of the intensity I_1 at the relaxation frequency increases by several times and the periodic low-frequency modulation of counterpropagating waves becomes less regular.

The self-modulation regime observed in this work has some specific features characteristic of the self-modulation regime of the second kind (the periodic low-frequency antiphase envelope and the self-modulation with the relaxation oscillation frequency). At the same time, there is an important difference: the variations in the intensities of counterpropagating waves in the case of the self-modulation regime of the second kind are almost identical (there exists only a delay by the half-period of self-modulation), while the self-modulation of the intensities of counterpropagating waves in the regime studied in this work is considerably asymmetric due to the amplitude nonreciprocity of the ring cavity. As the magnetic field direction changes to opposite, the considered regime is retained, but the waves change places.

4. Conclusions

Thus, our experimental studies of the nonlinear dynamics of a ring chip laser in an external static magnetic field inducing both the frequency and considerable amplitude nonreciprocities allowed us to observe a new quasi-periodic self-modulation regime of bidirectional lasing, which is characterised by the antiphase low-frequency envelope of the self-modulation oscillations of counterpropagating waves. This regime has some specific features typical for the self-modulation regime of the second kind, but differs from the latter by a significant asymmetry of the self-modulation of the intensities of counterpropagating waves due to the amplitude nonreciprocity of the ring cavity.

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