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Generation regimes of a solid-state coupled-cavity ring laser

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Abstract. **Based on the experimental studies we have shown that when an inhomogeneous magnetic field is applied to an active YAG : Nd crystal, a solid-state coupled-cavity ring laser is characterised by the following generation regimes: stationary unidirectional regime, self-modulation regimes of the first and second kinds, and dynamic chaos regime. Transitions between these generation regimes were carried out when the magnet was moved over the surface of the YAG : Nd single crystal, which made it possible to control the radiation dynamics.**

Keywords: *solid-state ring laser, coupled resonators, optical nonreciprocity, self-modulation oscillations, dynamic chaos.*

1. Introduction

Coupled-cavity ring lasers are of interest for gyroscope applications, since they make it possible to increase the sensitivity to rotation with increasing scale factor [1–6]. Investigations were performed for passive [1–3] and active [4–6] laser gyroscopes.

In solid-state ring lasers (SSRLs), due to the competition of counterpropagating waves, the stationary bi-directional regime is unstable and there arise self-modulation generation regimes. The dynamics of SSRL radiation and the possibility of controlling it have been studied in detail (see, e. g., review [7]). The generation regimes of coupled-cavity SSRLs are still scarcely studied. In papers [8, 9], the influence of coupled resonators on the characteristics of SSRL radiation in the self-modulation regime of the first kind was considered. The purpose of this paper is to experimentally study the generation regimes of a coupled-cavity SSRL that arise when an inhomogeneous magnetic field is applied to an active medium.

2. Experimental setup

The coupled-cavity SSRL in question is shown schematically in Fig. 1. The main cavity is a monolithic ring resonator made of a high-quality YAG : Nd single crystal. Such a resonator is usually used in ring-shaped chip lasers [7]. It has the shape of a prism with one spherical face (with a radius of curvature of 50 mm) and three flat faces of total internal reflection. The geometrical perimeter of the resonator is 2.8 cm, and the nonflatness angle of the resonator is 80°.

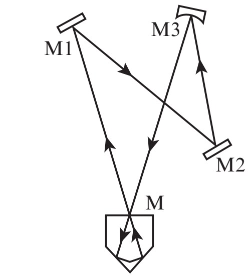

Figure 1. Schematic of a coupled-cavity ring laser.

The laser radiation emitted from the monolithic resonator through the dichroic mirror (M) applied to the face returns to the monolithic ring resonator with the help of three mirrors (M1, M2, and M3), which are part of an additional ring resonator (see Fig. 1). These mirrors have high reflection coefficients that are close to unity. Mirrors M1 and M2 are flat, and mirror M3 is spherical with a radius of curvature R = 50 cm. The length of the perimeter of the additional ring cavity is L_c = 86.5 cm. The SSRL is pumped by a semiconductor laser diode, whose radiation passes into a monolithic resonator through the face of the dichroic mirror (M).

On the upper surface of the prism (Fig. 2) there is a magnet (Mag), which has the form of a rectangular parallelepiped. During the experiment, the magnet was moved by means of a micrometric device.

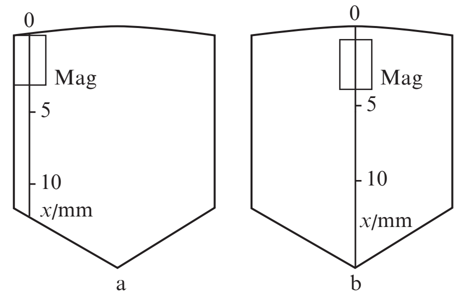

Figure 2. Two variants of moving the magnet along the upper surface of the YAG : Nd single-crystal prism: (a) along the edge and (b) through the centre of the prism; (Mag) is a magnet, and the x axis indicates the direction of its movement.

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3. Experimental results

In this paper, we studied experimentally the generation regimes in a coupled-cavity SSRL, which arise when an external inhomogeneous magnetic field is applied to a YAG : Nd single crystal. The investigations were carried out at a constant pump level, exceeding the pump above the threshold without an external resonator, $\eta = 0.08$. Analogous studies for an Nd : YAG ring chip laser were performed in [10].

Self-modulation regime of the first kind. In the absence of an external magnetic field, the SSRL under investigation was operated in the self-modulation regime of the first kind. The first experimental and theoretical studies of this regime in diode-pumped ring chip lasers were performed in Refs [11–14]. In the regime of the first kind, harmonic antiphase self-modulation oscillations of the intensities of counterpropagating waves are excited. Figure 3 shows two oscillograms of the intensity of one of the waves. Oscillogram (*1*) corresponds to a ring chip laser without an additional resonator; in this case, the amplitude of self-modulation oscillations is approximately half that of the two coupled resonators [oscillogram (*2*)]. The self-modulation frequency in the ring chip laser is f_m = 208 kHz. In the coupled-cavity SSRL, the frequency f_m is already 180 kHz.

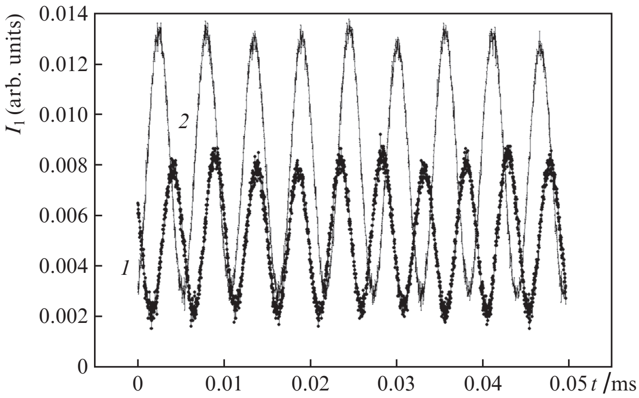

Figure 3. Oscillograms of the radiation intensity of one of the waves in the self-modulation regime of the first kind (see text).

By adjusting the perimeter of the additional resonator by the value on the order of the laser radiation wavelength, it is possible to reduce the amplitude of self-modulation oscillations and increase the frequency f_m [8, 9]. To carry out experimental studies, the perimeter length L_c was adjusted in such a way that the amplitude of self-modulation oscillations became maximal (at a fixed pump level). This adjustment of the additional resonator corresponds to the in-phase coupling of the two resonators [8, 9]. Note that in the present work it was possible to ensure a greater stability of the perimeter L_c than in [8], due to which the in-phase coupling of the resonators was preserved during the whole observation time (without jumps to the anti-phase coupling).

Self-modulation regime of the second kind. The magnet was moved either along the edge of the YAG : Nd single crystal surface (Fig. 2a) or through its centre (Fig. 2b). Let us discuss the results obtained for the first variant of the magnet displacement.

Due to the Faraday effect, when an external magnetic field is applied to the YAG : Nd single crystal, both the frequency and amplitude nonreciprocities of the ring resonator arise in the SSRL, which change as the magnet moves [7, 10]. At the initial position of the magnet corresponding to $x = 0$ (the spherical face of the prism coincides with the upper side of the magnet), the SSRL with two resonators operates in a steady-state unidirectional oscillation regime. The transition to this regime is obviously due to the amplitude nonreciprocity of the ring resonator, which arises from the Faraday effect, when an external magnetic field is applied.

The magnet was moved with a step $h = 1$ mm. At the positions of the magnet, $x = 0$ and 1 mm, a stationary regime of unidirectional generation is observed. With further displacement of the magnet ($x = 2$ and 3 mm), the self-modulation regime of the second kind arises in the SSRL with two resonators. As shown by experimental and theoretical studies [15–18], this regime exists in the SSRL at perimeter lengths $L_c \sim 1$ m. In ring chip lasers the perimeter is much smaller and the coupling of counterpropagating waves through backscattering is much larger, which leads to the fact that this regime cannot be observed in chip lasers. The situation changes in the presence of an additional resonator.

Figures 4a (at $x = 2$ mm) and 4b (at $x = 3$ mm) show the intensity oscillograms of one of the waves in the self-modulation regime of the second kind. In this regime, there occurs a low-frequency switching of the direction of the generated radiation at a frequency $f = 200$ Hz. As can be seen from Fig. 4b, with a change in the direction of radiation, a transient process arises, accompanied by damped relaxation oscillations.

When the magnet is subsequently moved along the edge of the prism, a steady-state unidirectional generation is observed in the region $x > 4$ mm.

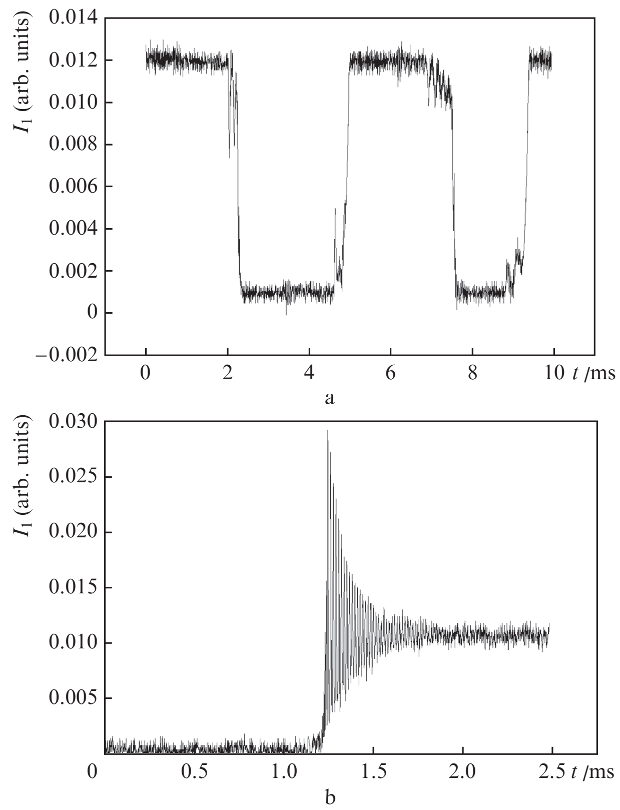

Figure 4. Oscillograms of the radiation intensity of one of the waves in the self-modulation regime of the second kind at x = (a) 2 and (b) 3 mm.

Dynamic chaos regime. In the second variant of moving the magnet (Fig. 2b), the following results are obtained. In the region of the magnet positions, $0 < x \leqslant 7$ mm, the coupled cavity SSRL operates in the regime of dynamic chaos. Figure 5 shows the time dependence of the intensity of one of the waves in this regime, and Fig. 6 shows the radiation intensity spectrum.

As seen in Figs 5 and 6, in the chaos regime the radiation has the form of a sequence of irregular spikes, and in the continuous intensity spectrum, wide maxima arise at frequencies that are multiples of the fundamental relaxation frequency $f_{r0} = 60$ kHz.

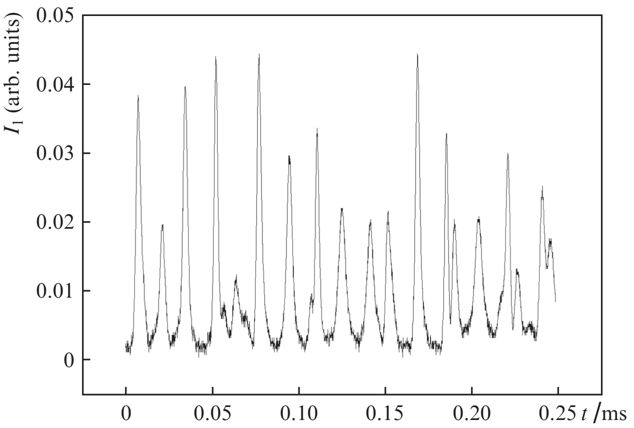

Figure 5. Oscillogram of the radiation intensity of one of the waves in the dynamic chaos regime.

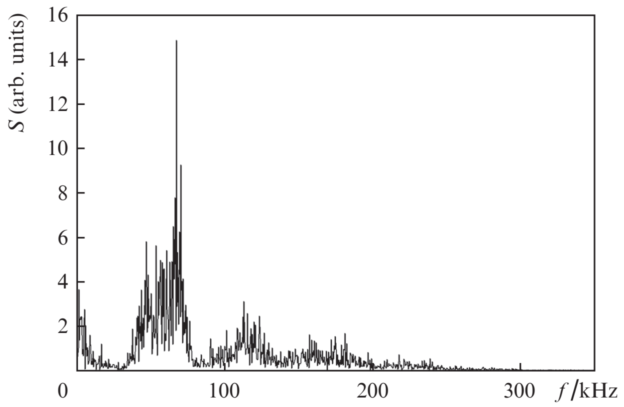

Figure 6. Radiation spectrum of one of the waves in the dynamic chaos regime.

At magnet positions in the region $x > 7$ mm, the self-modulation regime of the first kind is observed.

Thus, we have shown that when an inhomogeneous magnetic field is applied to a YAG : Nd crystal in a coupled-cavity SSRL, the following generation regimes can be realised: stationary unidirectional regime, self-modulation regimes of the first and second kinds, and dynamic chaos regime. The self-modulation regime of the second kind is observed only in the presence of an additional resonator; in a ring-shaped chip laser without an additional resonator, this generation regime is absent. When a magnet is moved over the surface of the YAG : Nd single crystal, the radiation dynamics can be controlled to choose between the indicated generation regimes.

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