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On the possibility of increasing the sensitivity to rotation with a constant magnetic field in a ring laser based on an Nd:YVO_4 crystal

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An Nd:YVO_4 ring laser operating in the regime of frequency locking of counterpropagating waves has an infinite locking region. In the present study, self-modulation lasing is established in such a laser by introducing a control element consisting of a quarter-wave plate and a magnetoactive crystal in an external magnetic field into the cavity. The modulation frequency of radiation intensity in this operating regime is proportional to the phase nonreciprocity of the ring cavity, which is induced, in particular, by rotation. It is demonstrated that the emission spectrum in the self-modulation regime is narrower than in the regime of frequency locking of counterpropagating waves.

Keywords: solid-state ring laser, frequency locking of counterpropagating waves, self-modulation lasing regime, optical phase nonreciprocity.

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1. Introduction

The construction of laser gyroscopes (LGs) based on solid-state ring lasers (SSRLs) is one of the research trends in laser gyroscopy. Most gyroscopy-oriented SSRL studies are focused on yttrium aluminum garnet (YAG) lasers. The frequency characteristics of Nd:YAG SSRLs operating in the counterpropagating wave beating regime are close to those achieved in high-accuracy gas LGs [1–3].

Yttrium vanadate YVO_4 ring lasers may be regarded as new and promising candidates for construction of LGs based on SSRLs. The cross section of the lasing transition at a wavelength of $1.06\,\mu$m in a Nd:YVO_4 crystal is 4.6 times larger than in Nd:YAG, providing an opportunity to lower the generation thresholds and reduce the length of the active region.

Bidirectional operation of an Nd:YVO_4 SSRL with passive locking of axial modes was investigated experimentally in [4,5]. Mode locking (ML) was achieved by introducing a nonlinear absorber into the cavity. In the ML regime, ultrashort light pulses propagate in opposite directions inside the ring cavity and overlap within the nonlinear absorber. Owing to backscattering in the absorber, strong coupling of counterpropagating waves was established, and a large locking region (about 10 deg/s) was formed. Beating of frequencies of counterpropagating waves was observed outside the locking region.

Experimental studies of bidirectional operation of Nd:YVO_4 SSRLs with free-running lasing were carried out in [6,7]. The following self-modulation lasing regimes were noted in [6]: (1) antiphase modulation of intensities of counterpropagating waves, (2) in-phase modulation of intensities of counterpropagating waves, and (3) dynamic chaos. The stationary regime of frequency locking of counterpropagating waves in an Nd:YVO_4 SSRL was studied experimentally in [7]. It was demonstrated that one of the counterpropagating waves gets suppressed with an increase in phase nonreciprocity in the locking regime, and this regime does not transition to beating. Self-modulation lasing regimes were also observed in [7], but, unlike the stationary regime of frequency locking of counterpropagating waves, they persisted only for a short period of time (on the order of a minute), and then the SSRL entered the stationary frequency locking regime again.

In the present study, a new way (using a constant magnetic field) to control the characteristics of an Nd:YVO_4 SSRL operating in the regime of frequency locking of counterpropagating waves is proposed and investigated experimentally.

2. Experimental setup

The examined SSRL with a planar four-mirror cavity is shown schematically in Fig. 1. The perimeter length of the ring cavity is $L_c = 90$ cm. Cavity mirrors M1 and M2 are planar, while M3 is a spherical mirror with curvature radius $R = 50$ cm. The fourth dichroic mirror (M4) is deposited onto the face of the yttrium vanadate Nd:YVO_4 laser crystal, which has the shape of a rectangular plate $5 \times 5 \times 2.5$ mm in size. The length of the active element is 2.5 mm. A semiconductor laser diode (Pump) is used for pumping. Its radiation enters the cavity through dichroic mirror M4 and is absorbed completely along the length of the active element.

This arrangement with one of the cavity mirrors deposited onto the surface of the active element offers several advantages. First, the intra-cavity space is not filled by the

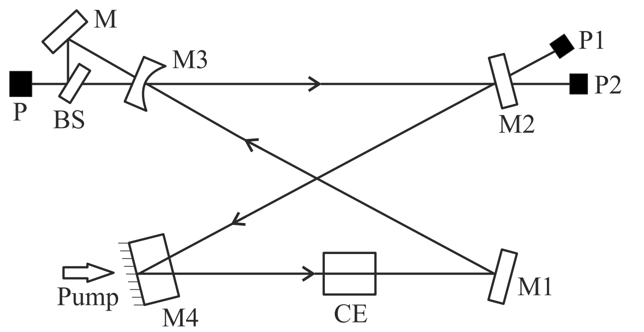

Figure 1. Diagram of the ring laser. M1, M2 — planar mirrors; M3 — spherical mirror with curvature radius $R = 50$ cm; M4 — yttrium vanadate Nd:YVO_4 crystal with a dichroic mirror deposited onto its surface; Pump — pumping beam; P1, P2 — laser radiation photodetectors; P — photodetector recording the mixing signal of two counterpropagating waves; and M, BS — mirror and beam-splitting plate for wave mixing.

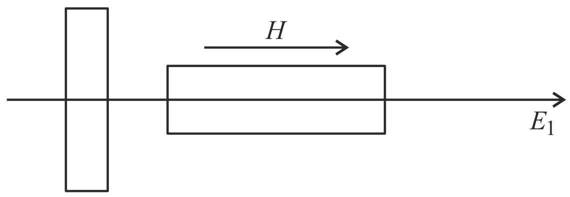

Figure 2. Diagram of the control element. $\lambda/4$ — quarter-wave plate; H — magnetoactive crystal in an external magnetic field.

active medium, and more room is left for other elements (for example, the control element (CE)). Second, pumping radiation is absorbed in the M4 plate and does not enter the cavity. Third, beams of counterpropagating waves generated inside the cavity are incident onto the surface of the active element at an angle differing from 90°, which suppresses their coupling through backscattering at this surface.

Laser radiation produced by the studied SSRL has a linear polarization directed at an angle of 90° to the cavity plane. Beams of counterpropagating waves are outcoupled from the ring cavity through mirror M2 and detected by photodetectors P1 and P2. A signal proportional to the sum of fields of counterpropagating waves $E_1 + E_2$ is fed to photodetector P via mirror M and beam-splitting plate BS. Photomixing signal $I_s = |E_1 + E_2|^2$ is read out from the output of this photodetector.

The SSRL parameters are adjusted using a magnetic field in the following way. Control element CE is positioned inside the cavity between mirrors M4 and M1 (Fig. 1). Its schematic diagram is shown in Fig. 2. This element consists of a quarter-wave plate ($\lambda/4$) and a bismuth germanate $Bi_4Ge_3O_{12}$ crystal [8] that features high magneto-optical activity. Magnetic field H is induced in this crystal by a solenoid. Our present experiments demonstrated that the orientation of the phase plate is of great importance. To characterize it, we introduce three-dimensional coordinate system xyz. Axis z coincides with the direction of propagation of the laser beam in the region between the plate and the bismuth germanate crystal, and axis y is perpendicular to the plane of the ring cavity. It was found that when the optical axis of the $\lambda/4$ plate is oriented parallel to the y axis, the CE used affects neither the intensity of generated counterpropagating waves nor the polarization of radiation, which is near-linear and directed along the y axis. The results reported below, which reveal a marked influence of CE on the process of SSRL lasing, were obtained with the optical axis of the $\lambda/4$ plate rotated by angle $\varphi = \pi/4$ in plane xy.

3. Experimental results

When the CE is not installed, the stationary regime of frequency locking of counterpropagating waves is established in the studied SSRL. The intensities of counterpropagating waves are constant (independent of time) in this regime, and the optical frequencies of fields are equal. As was demonstrated in [7], one of the counterpropagating waves gets suppressed with an increase in phase nonreciprocity of the ring cavity, but the locking regime is preserved and does not switch to the beat one.

The polarization of radiation with no CE is linear (the ratio of axes of the polarization ellipse is greater than 100) and orthogonal to the cavity plane. When the CE is introduced, the polarization becomes elliptical with an axial ratio of 6. The polarization ellipse is elongated in the direction orthogonal to the cavity plane.

With the solenoid coil current remaining within the $0 < J < J_c$ range, where $J_c = 0.72$ A, the SSRL with the CE inside the cavity operates in the stationary regime of frequency locking of counterpropagating waves. Figure 3 presents the oscilloscope records of intensities of counterpropagating waves I_1, I_2 at photodetectors P1 and P2 with current $J = 0$ (Fig. 3, *a*) and $J_c = 0.72$ A (Fig. 3, *b*) in the solenoid coil. These results were obtained with pumping P exceeding threshold level P_{th} by $\eta = P/P_{\text{th}} - 1 = 0.05$.

It can be seen from Fig. 3 that intensities I_1, I_2 do not depend on time in the regime of frequency locking of counterpropagating waves. One of the waves is suppressed when current J increases. No beating of frequencies of counterpropagating waves is observed at currents $0 < J < J_c$. As was demonstrated in [9], the phase difference of counterpropagating waves within the locking region depends on the angular velocity of rotation, allowing one to measure the angular velocities in this region. However, the examined lasing regime is not single-mode, which makes it significantly harder to perform such measurements. We used a different method, which relies on measurements of the frequency of self-modulation oscillations excited by the CE, to determine the rotation velocity.

With the pumping exceeding the threshold only slightly $(0.02 < \eta < 0.1)$, three longitudinal modes are excited in

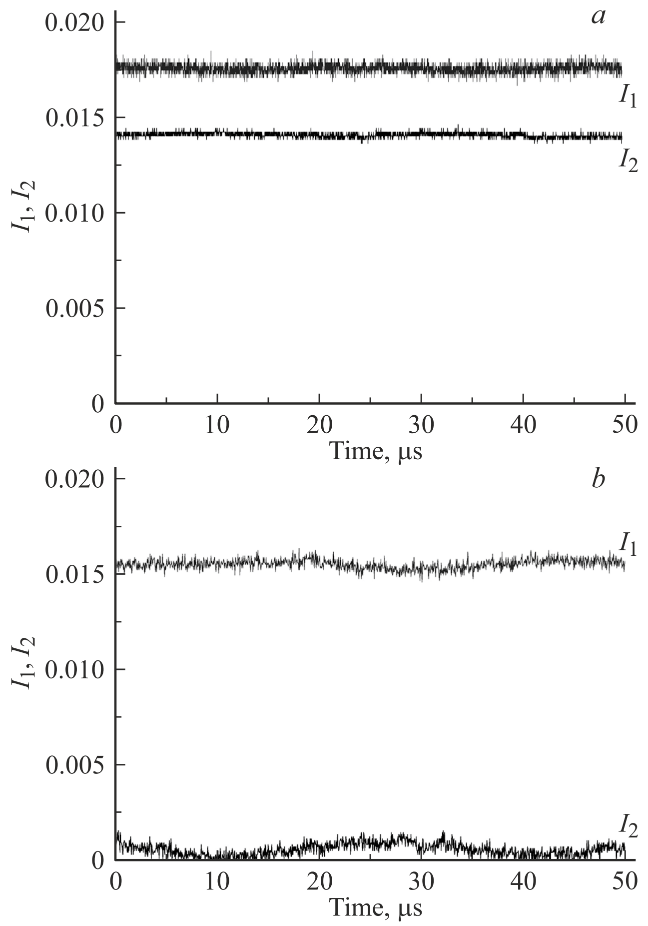

Figure 3. Oscilloscope records of counterpropagating wave intensities I_1, I_2 in the regime of frequency locking of counterpropagating waves at the following currents in the solenoid coil: $J = 0\,(a)$ and $J_c = 0.72\,\mathrm{A}$ (b).

the locking regime. Figure 4, a shows the $S(f)$ intermode beat spectra illustrating the presence of three longitudinal modes in this regime. The intermode beat frequency in the examined SSRL is $c/L = 315\,\mathrm{MHz}$.

The regime of frequency locking of counterpropagating waves turns out to be unstable at currents $0.72\,\mathrm{A} < J < 1.9\,\mathrm{A}$ in the solenoid coil, and the studied SSRL enters the self-modulation regime. Characteristic oscilloscope records of counterpropagating wave intensities I_1, I_2 and photomixing signal $I_s = |E_1 + E_2|^2$ in the self-modulation regime are presented in Fig. 5.

Sine modulation of counterpropagating wave intensities I_1, I_2 in the self-modulation regime is seen in Fig. 5. The modulation depth in photomixing signal I_s is significantly smaller than in the intensities. The lasing spectrum becomes narrower in transition to the self-modulation regime. It can be seen from Fig. 4 that at $\eta = 0.05$, three-mode lasing in the regime of frequency locking of counterpropagating waves gives way to two-mode lasing in the self-modulation regime.

The obtained results revealed that frequency ω_m, of self-modulation oscillations depends on current J in the solenoid coil. This dependence (see Fig. 6) is near-linear.

At currents $J > 1.7\,\mathrm{A}$ in the solenoid coil, the regime of frequency locking of counterpropagating waves is established once again in the SSRL.

4. Discussion

Let us consider the interaction of counterpropagating waves in the SSRL on the qualitative level. In the regime of frequency locking of counterpropagating waves, their frequencies are equal. The population inversion is burned down in a spatially non-uniform way in the field of two counter-propagating waves with equal frequencies, and periodic population inversion gratings with a period of $\lambda/4$ emerge. Owing to Bragg reflections off these gratings, the gain factors for counterpropagating waves in the SSRL become unequal: the wave with a higher intensity has a higher gain factor. This inequality of

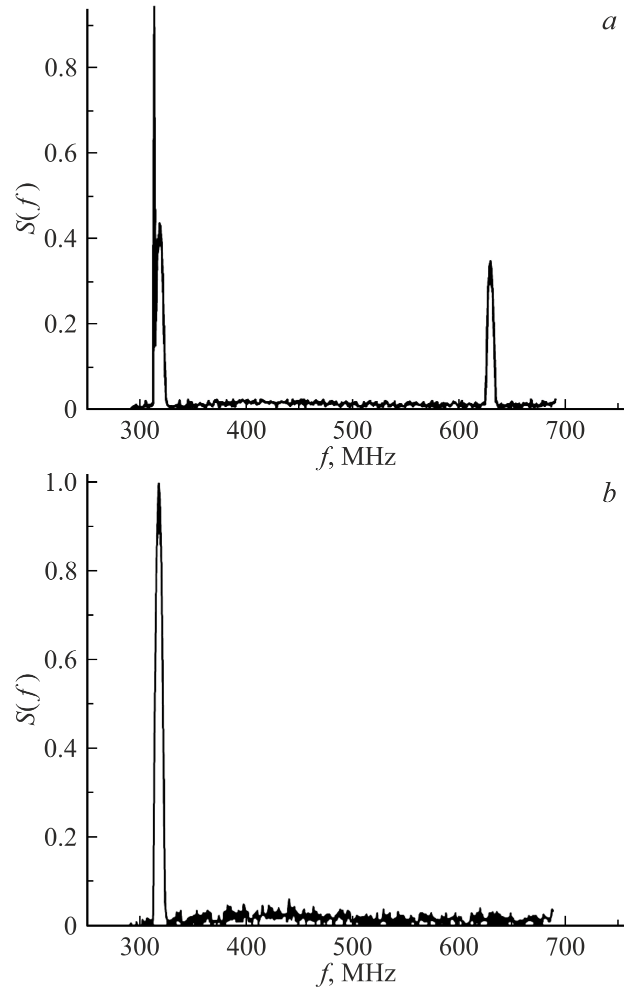

Figure 4. Spectra of intermode beats of radiation intensity $S(f)$ in the regime of frequency locking of counterpropagating waves (a) and the self-modulation regime (b).

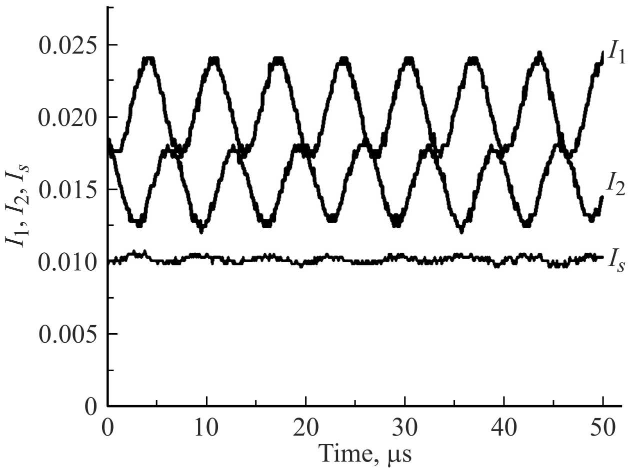

Figure 5. Oscilloscope records of counterpropagating wave intensities I_1, I_2 and photomixing signal I_s in the self-modulation lasing regime.

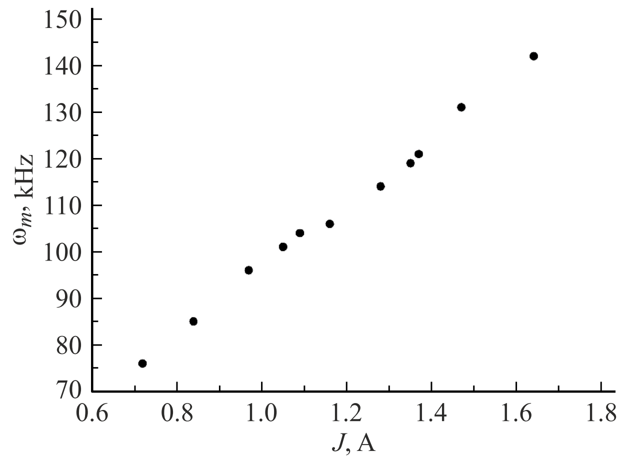

Figure 6. Dependence of self-modulation frequency ω_m on current J in the solenoid coil.

gain factors should theoretically lead to suppression of one of the counterpropagating waves. However, as was demonstrated in [10], the coupling of counterpropagating waves through backscattering inside the cavity, which stabilizes bidirectional lasing and may induce a stationary regime of frequency locking of counterpropagating waves, has the capacity to counteract this suppression. If the CE is lacking, this lasing regime persists in the studied SSRL with increasing phase nonreciprocity of the ring cavity [7].

As was demonstrated earlier in [11,12], a single-mode self-modulation regime (SMR) of the first kind may be excited in the SSRL in the parameter region where the backscattering coupling is insufficient to ensure the stability of bidirectional lasing. The SMR observed in the present study is close in nature to an SMR of the first kind. Sine and nearly antiphase self-modulation of counterpropagating wave intensities is observed in both regimes. However, a significant difference is also evident. With close average values of the intensities of counterpropagating waves, the depth of self-modulation of these intensities in an SMR of the first kind is one hundred percent. On the contrary, the studied SSRL features a small depth of intensity modulation when the values of intensities I_1, I_2 are almost equal (Fig. 5). This contradiction may be eliminated if one considers that the observed SMR features two-mode lasing. Let us assume that one of the two modes (the first one) generates in the counterpropagating wave locking regime, while the second mode operates in the SMR of the first kind. The experimentally observed small modulation depth at close average intensity values then becomes feasible if the second mode is significantly less intense than the first one.

The frequency of antiphase self-modulation of intensities of counterpropagating waves in an SMR of the first kind depends on phase nonreciprocity Ω of the ring cavity in the following way [11,12]:

$$\omega_m = \sqrt{\omega_m(0)^2 + \Omega^2}, \tag{1}$$

where $\omega_m(0)$ is the self-modulation frequency at zero phase nonreciprocity, $\Omega = 0$. A near-linear dependence of the self-modulation frequency on Ω is obtained at $\Omega \gg \omega_m(0)$.

As optical phase nonreciprocity Ω increases, the SSRL undergoes a transition from an SMR of the first kind to the stationary regime of frequency locking of counterpropagating waves [13]. This is consistent with the observed transition of the SMR to the locking regime at high phase nonreciprocity values.

Phase nonreciprocity Ω was adjusted in our experiments by a magnetic field through the Faraday effect. A change in the Ω value may also be induced by rotation through the Sagnac effect [14,15]. Thus, self-modulation oscillation frequency ω_m provides data on the angular velocity of rotation. It should be noted that the effective area of the closed circuit composed of two triangles with opposite beam paths is near-zero in SSRL cavity arrangements close to the one shown in Fig. 1. The optical nonreciprocity caused by rotation then also turns out to be close to zero. In order to increase the sensitivity to rotation, one needs to modify the ring cavity arrangement so that the areas of triangles with opposite beam paths become significantly different.

5. Conclusion

An SSRL with a near-linear dependence of the self-modulation frequency on phase nonreciprocity Ω of the cavity was obtained with the use of a control element in an Nd:YVO$_4$ SSRL operating in the regime of frequency locking of counterpropagating waves. With the CE introduced, the polarization of radiation changed from linear to elliptical. The radiation spectrum in the SMR turned out to be narrower than the spectrum recorded in the regime of frequency locking of counterpropagating waves.

Conflict of interest

The authors declare that they have no conflict of interest.

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