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Interaction of counterpropagating waves in a Nd:YVO_4 ring laser

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Abstract. **We have experimentally studied the stationary regime of bidirectional lasing and self-modulation regimes in a Nd:YVO_4 solid-state ring laser (SSRL) in the presence of phase nonreciprocity of the ring cavity. It is found that the emission spectrum in the regime of frequency matching of counterpropagating waves is much narrower than in a Nd:YAG SSRL. When the phase nonreciprocity increases in the matching regime, one of the counterpropagating waves is suppressed, and this regime does not switch to the beat regime.**

Keywords: *solid-state ring laser, frequency matching of counterpropagating waves, optical nonreciprocity, self-modulation oscillations.*

1. Introduction

The development of laser gyroscopes (LGs) based on a solid-state ring laser (SSRL) makes it possible to eliminate some of the disadvantages inherent in gyroscopes based on a ring gas laser (the presence of a gas-filled volume in the cavity, the need to maintain a gas discharge). In SSRL research focused on applications in gyroscopy, most works are devoted to yttrium–aluminium garnet (YAG) crystal-based lasers. Note that Nd:YAG SSRLs operating in the regime of counterpropagating wave beats demonstrated frequency characteristics that are close to those attained in high-precision gas LGs [1, 2].

A ring laser based on a YVO_4 yttrium vanadate crystal can be considered as one of the promising options for a generator in a SSRL-based LG, since the cross section of the laser transition at a wavelength of 1.06 μm in the Nd:YVO_4 crystal is 4.6 times larger than in Nd:YAG, which makes it possible to reduce the lasing thresholds and the active region length.

In works [3, 4], in a Nd:YVO_4 SSRL, bidirectional lasing in the regime of passive locking of axial modes was experimentally investigated. The mode locking (ML) occurred when a nonlinear absorber was introduced into the cavity. In the ML regime, ultrashort light pulses propagate in opposite directions inside the ring cavity, overlapping inside the nonlinear absorber. Due to backscattering, a strong coupling of counterpropagating waves and a large lock-in area (of the order of 10 deg s^{-1}) appear in the absorber, while the beat regime is observed outside the lock-in region. Similar results for bidirectional lasing in the ML regime were obtained in work [5].

Experimental studies of bidirectional lasing in a Nd:YVO_4 SSRL in the case of free lasing, conducted in work [6], have shown that the competition of counterpropagating waves leads to the appearance of the following self-modulation lasing regimes: the regime of antiphase modulation of the intensities of counterpropagating waves, the regime of in-phase modulation of the intensities of counterpropagating waves, and the regime of dynamic chaos.

In contrast to Nd:YAG SSRLs, which have been the subject of numerous theoretical and experimental studies of lasing regimes, bidirectional YVO_4 ring lasers have been studied to a much lesser extent. The aim of this work is to experimentally study the regimes of free lasing in bidirectional Nd:YVO_4 SSRL.

2. Experimental setup

The SSRL under study with a flat four-mirror cavity is schematically shown in Fig. 1. The cavity mirrors M1 and M2 are flat, and M3 is a spherical mirror with a curvature radius of R = 50 cm. The fourth dichroic mirror is deposited on the face of the Nd:YVO_4 laser crystal (LC), which has the shape of a rectangular plate 5 × 5 × 2.5 mm in size; the active element length is 2.5 mm. Pumping is carried out by a semiconductor laser diode; its radiation passes into the cavity through this dichroic mirror and is completely absorbed along the active element length.

The scheme in which one of the cavity mirrors is deposited on the active element surface has certain advantages. First, the space inside the cavity is not occupied by the active

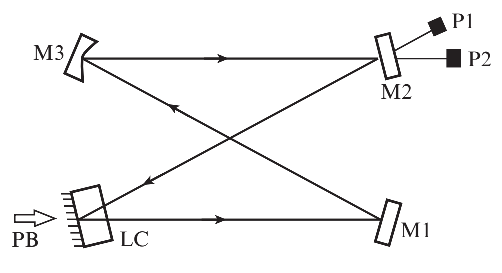

Figure 1. Scheme of a ring laser: (M1, M2) flat mirrors; (M3) spherical mirror with a curvature radius R = 50 cm; (LC) Nd:YVO_4 yttrium vanadate crystal with a dichroic mirror deposited on its surface; (PB) pump beam; (P1, P2) laser radiation photodetectors.

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medium, and there is more space to accommodate other elements (for example, the Faraday element). Second, the pump beam (PB) of the laser diode is absorbed by the LC plate and does not enter the cavity. Third, the beams of counterpropagating waves generated inside the cavity fall onto the active element surface at an angle different from 90°, which reduces the coupling of counterpropagating waves through backscattering on this surface.

The laser radiation generated in the SSRL under investigation has a linear polarisation directed at an angle of 90° to the cavity plane. The beams of counterpropagating waves are outcoupled from the ring cavity through mirror M2 and are recorded by photodetectors P1 and P2. The perimeter length of the ring cavity is $L_c = 90$ cm.

In some experiments, to control the phase nonreciprocity of the ring cavity, a phase Faraday nonreciprocal element (PFNRE) was placed inside the cavity between the mirror deposited on the LC and mirror M1 (see Fig. 1), the operation of which is explained in Fig. 2.

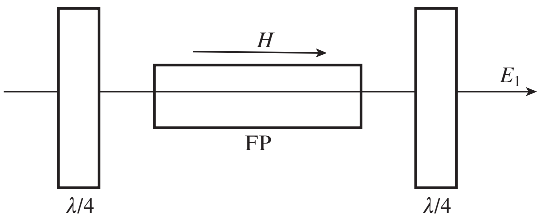

Figure 2. Scheme of a phase Faraday nonreciprocal element: ($\lambda/4$) quarter-wave plate; (FP) Faraday phase shifter (bismuth germanate crystal in the magnetic field of the solenoid H); E_1 is the transmitted wave.

The linearly polarised wave E_1, having passed through a quarter-wave plate $\lambda/4$, turns into a circularly polarised wave and falls on the $Bi_4Ge_3O_{12}$ crystal [7], which has a high magneto-optical activity. In this crystal, placed in a solenoid that creates a magnetic field, the counterpropagating waves receive additional phase shifts $\Delta\varphi_{1,2}$ of the opposite sign ($\Delta\varphi_1 = -\Delta\varphi_2$), proportional to the magnitude of the magnetic field H. After leaving the bismuth germanate crystal, the circularly polarised wave passes through another $\lambda/4$ plate and becomes linearly polarised again. Such a nonreciprocal element creates a phase optical nonreciprocity $\Omega = 2\,\Delta\varphi_1/T$ in the cavity, where T is the time the round-trip transit time for the light in the cavity.

3. Counterpropagating wave matching regime

In the SSRL under study, stationary generation of two counterpropagating waves with constant intensities was observed. The optical frequencies of the fields of counterpropagating waves turn out to be equal, and this regime is commonly called the counterpropagating wave matching regime. In the case of equal intensities of counterpropagating waves, a standing wave is formed in the ring cavity.

Using an AKS-1301 spectrum analyser, we found that the lasing on a single axial mode in this regime only exists in the region of small excess of the pump power P above the threshold level P_{th}, namely, for $\eta = P/P_{th} - 1 < 0.02$. In this region, there are no high-frequency components in the intensity spectra of counterpropagating waves at the intermode beat frequency $c/L_c = 335$ MHz. In the region of exceeding the threshold $0.02 < \eta < 0.1$, two longitudinal modes are excited, and a component at the intermode beat frequency appears in the wave intensity spectra. At excess values of $\eta > 0.1$, components at frequencies of 335 and 670 MHz are observed in the radiation spectra, which indicates the excitation of three longitudinal modes in this region.

Figure 3 shows the intensity oscillograms of the counterpropagating waves at $\eta = 0.05$. It can be seen that the intensities I_1 and I_2 of the counterpropagating waves are close in magnitude. In the SSRL under investigation, high stability of the radiation intensities I_1 and I_2 was observed in the regime of matching of the counterpropagating wave frequencies.

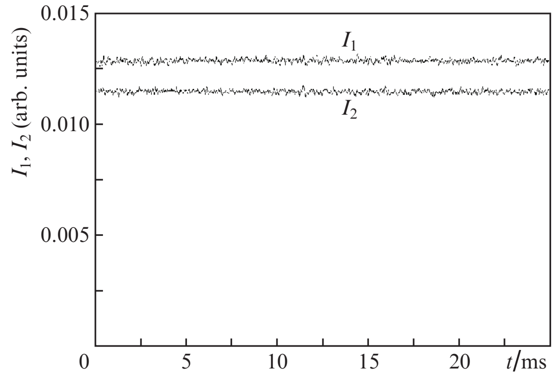

Figure 3. Oscillograms of counterpropagating wave intensities in the matching regime at $\eta = 0.05$.

4. Effect of phase nonreciprocity on the matching regime

In this work, we experimentally investigated the effect of phase nonreciprocity of the ring cavity on the counterpropagating wave matching regime. To create a phase nonreciprocity, an PFNRE was placed inside the ring cavity (see Fig. 2). A similar scheme for a Nd:YAG SSRL with a Faraday nonreciprocal element is described in work [8].

Figure 4 shows the dependence of the intensities I_1 and I_2 of the counterpropagating waves on the current J in the solenoid that forms a magnetic field in the PFNRE for the counterpropagating wave matching regime in the SSRL under consideration. It can be seen that as the phase nonreciprocity which is proportional to the current J increases, one of the counterpropagating waves is suppressed. The intensity difference changes the sign when the direction of the current changes: for positive J, the wave with I_1 is suppressed, and for negative J, the wave with I_2 is suppressed. These studies have shown that with increasing phase nonreciprocity, the SSRL in question is in the matching regime and does not switch to the beat regime.

Let us explain qualitatively the phenomena occurring in the SSRL operating in the regime of frequency matching of counterpropagating waves. In the SSRL active medium, the gain line is homogeneously broadened, and the counterpropagating wave frequencies in the matching regime are equal to each other. Therefore, in the field of two counterpropagating waves having equal frequencies, the population inversion burns out spatially inhomogeneously and there appear periodic population inversion lattices with period $\lambda/2$. As a result,

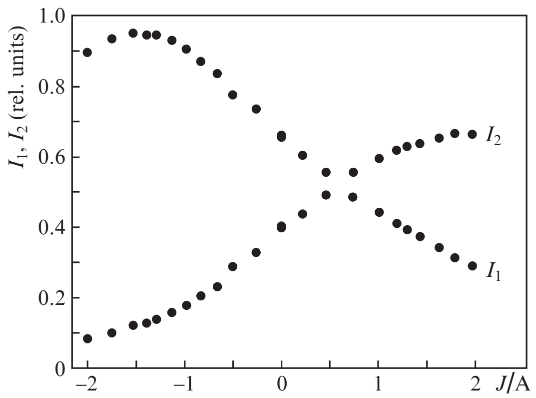

Figure 4. Dependence of the counterpropagating wave intensities on the current in the coil producing the magnetic field.

in SSRLs, due to Bragg reflections on these lattices, the gains for the counterpropagating waves become unequal: a wave with a higher intensity has a higher gain. Such an inequality in the gains should have led to the suppression of one of the counterpropagating waves. However, this is prevented by the coupling of counterpropagating waves due to backscattering inside the cavity. If the backscattering coupling is strong enough, the matching regime becomes stable.

Now let us consider qualitatively the effect of phase optical nonreciprocity on the matching regime. In the case of a sufficiently strong coupling that ensures the standing wave stability, the inequality of the intensities of the counterpropagating waves increases with increasing phase optical nonreciprocity (one wave increases while the other is suppressed). In this case, the phase difference of the counterpropagating waves remains virtually the same. With a sufficiently large phase nonreciprocity, one of the waves is almost completely suppressed; however, the phase difference of the counterpropagating waves does not change so much that the matching regime ceases to exist and the regime of beating of the counterpropagating waves appears. This regime with an unlimited matching bandwidth is typical of SSRLs; it was first observed in a Nd:YAG ring laser in work [9].

5. Self-modulation regime of the second kind

By changing the alignment of the laser's ring cavity (at small rotations and displacements of the cavity mirrors), lasing in the SSRL under study can be achieved in two self-modulation regimes: in the self-modulation regime of the second kind and in the regime of periodic in-phase self-modulation of the intensities of counterpropagating waves. The self-modulation regime of the second kind (sometimes also called the regime of low-frequency switching of the SSRL lasing direction) is well known from studies of Nd:YAG SSRLs (see review [10]). This regime can occur when the backscattering coupling is insufficient to ensure the stability of the counterpropagating wave matching regime but leads to instability of the regime of stationary unidirectional lasing. These conditions are satisfied either with a sufficiently large detuning of the lasing frequency from the gain line centre, or in the presence of a fine structure of the gain line [11, 12] stipulated by the presence of two close lines in the Nd:YAG luminescence spectrum. Figure 5 shows oscillograms of the counterpropagating wave intensities in the self-modulation regime of the second kind for the studied Nd:YVO$_4$ SSRL. It can be seen that at a time interval of approximately 0.5 ms, the SSRL lasing is close to unidirectional. Then the intensities of the counterpropagating waves begin to equalise, and the weak wave continues to grow even after the intensities become equal. As a result, there is a periodic low-frequency change in the direction of unidirectional lasing.

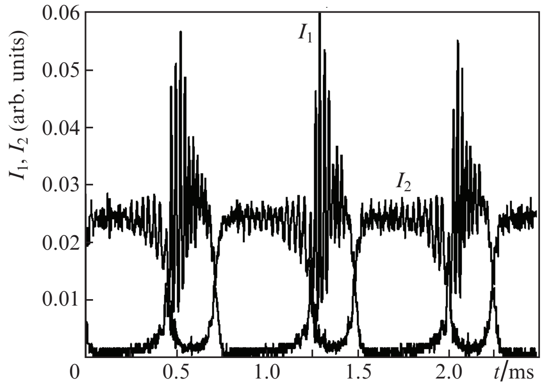

Figure 5. Oscillograms of counterpropagating wave intensities in the self-modulation regime of the second kind at $\eta = 0.05$.

In contrast to the stationary regime of counterpropagating wave frequency matching, in the laser under study, the self-modulation regime of the second kind exists for a short time interval (about a minute), after which it switches to the stationary regime of counterpropagating wave matching. Apparently, this is due to the fact that the region of existence of such a self-modulation regime is rather narrow, and the SSRL leaves it due to the thermal rearrangement of the ring cavity.

6. In-phase self-modulation regime

The regime of periodic in-phase self-modulation in the Nd:YAG SSRL was observed in work [13] when creating an asymmetric coupling of counterpropagating waves using an additional mirror located outside the cavity and returning one of the beams back to the cavity. In-phase self-modulation of intensities is associated with self-excitation of relaxation oscillations due to instability of stationary bidirectional lasing. Figure 6 shows the intensity oscillograms of counterpropagating waves in the in-phase self-modulation regime for the Nd:YVO$_4$ SSRL under study. The frequency of relaxation oscillations is $f = 65$ kHz.

This self-modulation regime, as well as the self-modulation regime of the second kind, can be observed in the SSRL under study for a short time interval (about a minute) after tuning the cavity to the region of its existence.

7. Self-modulation regime of the first kind

The self-modulation regime of the first kind, characterised by antiphase sinusoidal self-modulation of the counterpropagating wave intensities, was obtained in the SSRL under study by increasing the coupling of counterpropagating waves due to backscattering. To do this, a garnet crystal was placed inside the ring cavity. There was no pump radiation

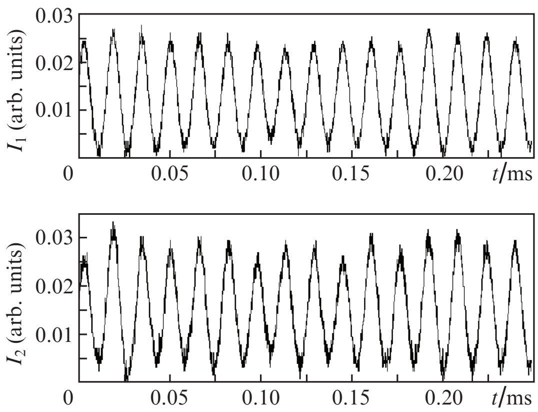

Figure 6. Oscillograms of counterpropagating wave intensities in the regime of periodic synchronous self-modulation at $\eta = 0.05$.

in this crystal, and it played the role of an additional source of backscattering in the cavity. The frequency of antiphase self-modulation of the counterpropagating wave intensities at a small rotation of the crystal garnet varied in the range of 50–500 kHz. The oscillograms of the counterpropagating wave intensities in the self-modulation regime of the first kind with the self-modulation frequency $f_{sm} = 83$ kHz are shown in Fig. 7.

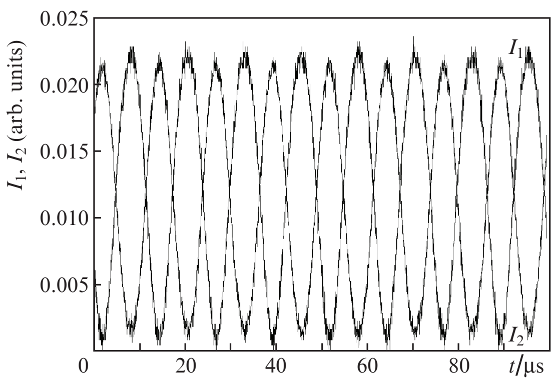

Figure 7. Oscillograms of counterpropagating wave intensities in the self-modulation regime of the first kind at $\eta = 0.05$.

As previously conducted studies have shown (see, for example, review [10]), this regime occurs in SSRLs when the coupling of counterpropagating waves through backscattering is close to conservative (scattering on the refractive index inhomogeneities) and the coupling value is insufficient to ensure the stability of stationary bidirectional lasing. In a stationary SSRL (with phase nonreciprocity of the cavity $\Omega = 0$), the frequency ω_{sm} of self-modulating oscillations is equal to the modulus of the feedback coefficients m. The dependence of the frequency ω_{sm} on the phase nonreciprocity of the ring cavity is determined by the approximate formula $\omega_{sm} = \sqrt{m^2 + \Omega^2}$. A simple qualitative explanation of this self-modulation regime was given in [14], where it was considered as a stationary two-mode lasing regime. The harmonic modulation of the radiation intensity in this regime is the result of the beating of two modes.

8. Conclusions

Experiments have shown that in the absence of any additional elements inside the ring cavity, the SSRL under study operates in a stationary regime of counterpropagating wave matching. This regime was previously observed in SSRLs based on a Nd : YAG crystal; however, the emission spectrum in this regime for the Nd : YAG laser turned out to be much wider. A significant narrowing of the lasing spectrum is probably due to the small length (2.5 mm) of the Nd : YVO_4 laser crystal.

When the phase nonreciprocity increases in the matching regime, one of the counterpropagating waves is suppressed, and this regime does not switch to the beat regime. For such a transition in the studied SSRL, it is necessary to weaken the competition of counterpropagating waves (for example, using a feedback circuit, as was done in works [1, 2]).

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