Width of synchronization band in a solid-state ring laser

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We investigated the synchronization regimes in a solid-state ring laser. It was established that: 1) unlike in a gas laser, there are synchronization regimes that do not go over into the beat regime with increasing revolution velocity and, 2) a transition of self-modulation regimes to the synchronization regime is possible at high revolution velocities.

1. Ring lasers (RL) are successfully used to measure small speeds of revolution. The measurements are usually carried out in a beat regime, i.e., outside the synchronization band of the opposing waves. Consequently, one of the most important parameters of the ring laser is the width Ω_0 of the synchronization band. For a gas ring lasers (GRL), the dependence of Ω_0 on the laser parameters has been investigated in detail in[1], whereas for the case of solid-state ring lasers (SRL) investigations of this kind have only just been started.[2]

We report here a theoretical and experimental investigation of the synchronization regime of the opposing waves in SRL. It is shown that the dependence of Ω_0 on the laser parameters is essentially different from the corresponding dependence in GRL. The theoretical analysis is carried out under the assumption that the lasing regime is single-mode, that the Q's of the resonator are the same for the opposing waves, and that the wave frequencies are close to the center of the gain line.

2. One feature possessed only by SRL is the existence of opposing-wave synchronization regimes that do not go over to the beat regime with increasing speed of revolution.

In SRL at rest, the regime of synchronization of the opposing waves is stable at[2]

$$m\left|\sin\frac{\theta_1-\theta_2}{2}\right| > \frac{1}{3}\frac{\omega}{Q}\eta . \qquad (1)$$

Here $\theta_1-\theta_2\equiv 2\delta$ is the phase difference between the feedback coefficients, and ω/Q is the resonator bandwidth. The moduli of the feedback coefficients m are assumed to be equal, and the excess of the pump level over threshold η is assumed to be small ($\eta \ll 1$). We consider the case when the coupling coefficients are nearly complex-conjugate ($\theta_1-\theta_2 \ll 1$). In accordance with (1), the synchronization regime can be stable only in the presence of "strong" feedback ($\epsilon \equiv \omega\eta/Qm \ll 1$). In this case it is possible to obtain analytically a solution that describes the synchronization regime of the opposing waves:

$$aE_{1,2}^2 = \frac{\sqrt{m^2+\Omega^2}\pm\Omega}{3m^2+2\Omega^2}\left[\frac{\epsilon-|\delta|}{\epsilon-\eta|\delta|}\sqrt{m^2+\Omega^2}+\frac{\delta}{\epsilon-\eta|\delta|}m\right]$$

$$\sin\left(\Phi-\frac{\theta_1+\theta_2}{2}\right) = -\Omega\,\frac{m[\epsilon-|\delta|]-2\delta\sqrt{m^2+\Omega^2}}{3m^2+2\Omega^2} \ll 1 . \qquad (2)$$

The solution (2) was obtained in first-order approximation in the small parameters ϵ and δ. Here $aE_{1,2}^2$ are the dimensionless intensities of the opposing waves (a is the saturation parameter), $\Phi=\phi_1-\phi_2$ is the phase difference of the waves, and Ω is the difference between the natural frequencies of the resonator for the opposing waves. An analogous strong-coupling solution exists also for GRL, and is stable within a synchronization band $\Omega_0=m/\sqrt{2}$.[1] At $|\Omega|>\Omega_0$, the beat regime sets in. In SRL, the condition for the stability for the synchronization regime is essentially different, owing to the large inverted-population relaxation time. This condition takes the form

$$[\epsilon-|\delta|]m-2|\delta|\sqrt{m^2+\Omega^2}<0 . \qquad (3)$$

It follows from (3) that if the synchronization regime is stable in the SRL at rest ($\epsilon<3|\delta|$), then it remains stable at all speeds of revolution. Thus, no beat regime can occur in the SRL in this case. In the regime of synchronization of the opposing waves, in accordance with (2), one of the opposing waves becomes suppressed as Ω is increased (Fig. 1).

If the synchronization regime is unstable in the SRL ($\epsilon>3|\delta|$), then according to (3), starting with the values

$$|\Omega|>\Omega_1=\frac{\omega}{Q}\sqrt{\eta^2-2\eta m|\delta|-3m^2\delta^2}/2m|\delta|$$

this regime becomes stable. In this case self-modulation generation takes place at $|\Omega|<\Omega_1$. With increasing

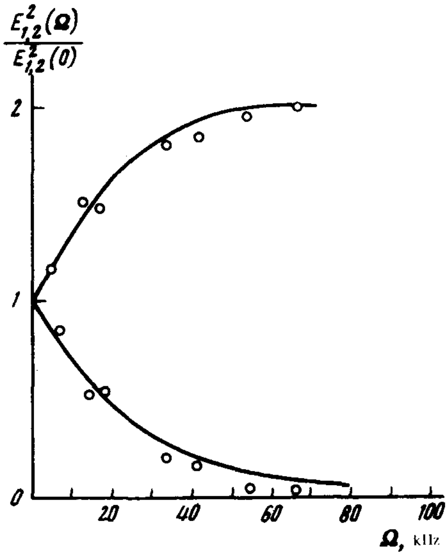

FIG. 1. Circles—experimental points, curves—theoretical ($mQ/\omega=0.8$, $\delta=0.05$, $\eta=0.1$).

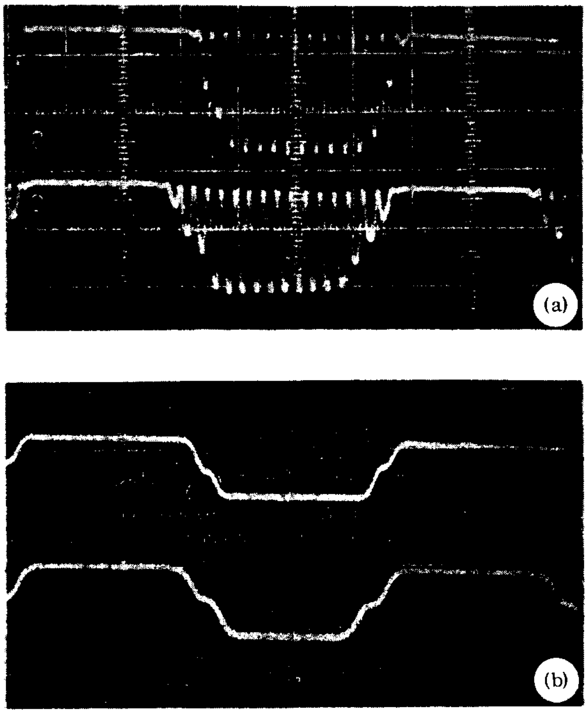

FIG. 2. a) $\Omega = 0$, b) $\Omega = 220$ kHz. Sweep 200 μsec/div.

speed of revolution, it goes over into the synchronization regime.

At coupling coefficient values close to anticomplex-conjugate ($\theta_1 - \theta_2 = \pm\pi$) the regime of opposing-wave synchronization was investigated in[2]. In this case the synchronization band of the SRL has a width $\Omega_0 = [m^2 - (\omega\eta/Q - m)^2/4]^{1/2}$. At $|\Omega| > \Omega_0$, the beat regime sets in.

3. Experimental investigations were carried out with a cw YAG:Nd^{3+} SRL. The coupling of the opposing waves was varied by bleaching the end faces of the crystal, by using crystals with Brewster end faces, and by tuning the resonator.[2]

When crystals with nonreflecting (residual reflection coefficient $\lesssim 0.4\%$) and Brewster end faces were used, the lasing regimes of the SRL depended on the magnitude and phase of the coupling coefficient, which in turn were determined by the tuning of the resonator. At definite tunings, a synchronization regime exists in the immobile SRL, and this regime does not change into a beat regime when the speed of revolution is increased. At sufficiently large speeds, one of the opposing waves is suppressed (Fig. 1).

By varying the resonator tuning it is possible to obtain synchronization regimes with finite width of the synchronization band Ω_0, which go over at $|\Omega| > \Omega_0$ into the beat regime. The width of the synchronization band, depending on the resonator tuning, ranged from several kHz to 2 MHz. When crystals with end faces cut at the Brewster angle were used, Ω_0 ranged from 1 to 20 kHz. A certain suppression of one of the opposing waves was observed within the locking region (the wave usually suppressed was that propagating against the direction of resolution). On going outside the locking region, the intensity of the opposing waves became jumpwise equalized and turned out to be modulated in counterphase at a frequency coinciding with the beat frequency observed when the opposing waves were shifted. It should be noted that near the locking boundary the beat frequency exceeded somewhat the difference between the natural frequencies Ω of the resonator.

At certain resonator tunings, a self-modulation lasing regime was observed in the SRL at rest (Fig. 2a; the radiation was modulated with a revolving blade). The frequency of the self-modulation oscillations increases with increasing speed of revolution and their amplitude decreases. At sufficiently large speeds, the self-modulation regime goes over into the regime of synchronization of the opposing waves (Fig. 2b).

Thus, the foregoing theoretical analysis is in sufficiently good agreement with the results of the experimental investigations.

[1]Volnovye i fluktuatsionnye protsessy v lazerakh (Wave and Fluctuation Processes in Lasers), edited by Yu. L. Klimontovich, Moscow, Nauka, 1974.

[2]E. L. Klochan, L. S. Kornienko, N. V. Kravtsov, E. G. Lariontsev, and A. N. Shelaev, Zh. Eksp. Teor. Fiz. 65, 1344 (1973) [Sov. Phys.-JETP 38, 669 (1974)].