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Dynamics of a bipolarised Nd:YAG laser with partially polarised pump radiation

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Abstract. **We propose a model of a bipolarised Nd:YAG laser with partially polarised pump radiation, providing competitive amplification of polarisation modes. A new type of instability is predicted, similar to the one that was first observed in [1]. The possibility of experimental verification of predictions is discussed.**

Keywords: *laser, polarisation mode, induced gain anisotropy, relaxation oscillations.*

1. Introduction

The model proposed in [1, 2], which takes into account the real orientations of active centres in the unit cell of yttrium aluminium garnet, describes well the main features of the induced gain anisotropy effect and low-frequency dynamics of solid-state lasers, observed in experiments [3–5]. The new type of instability predicted by this model is due to the presence of two orthogonally polarised types of absorbing dipole transitions. For experimental verification of the predictions of the developed theory, it was proposed to use a wavelength-tunable pump laser in order to be able to control the contributions of the π- and σ-transitions to the pumping process.

In this paper, we consider the possibility of using partially polarised pump radiation by adding a second source orthogonally polarised to the first radiation source. Thus, in contrast to the two orthogonal absorption channels associated directly with the active medium and considered in [1], we propose to use two orthogonally polarised external pump sources in the presence of only one type of absorbing transitions (either π- or σ-transition).

2. Unpolarised pumping

Partially or completely unpolarised radiation can be modelled using two orthogonally polarised radiation sources. By controlling the radiation intensities of these sources, it is possible to control the degree of polarisation of the pump radiation. The combined pump radiation field directed along the resonator axis coinciding with the crystallographic X axis is introduced as the sum of two fields (Fig. 1):

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$$\boldsymbol{E}_{\rm p} = \boldsymbol{E}_{\rm p}^0 + \boldsymbol{E}_{\rm p}^{90},$$

where

$$\boldsymbol{E}_{\rm p}^0 = |\boldsymbol{E}_{\rm p}^0|\boldsymbol{e}_{\rm p}^0 = |\boldsymbol{E}_{\rm p}^0|(\boldsymbol{y}^0\cos\Psi_{\rm p} + \boldsymbol{z}^0\sin\Psi_{\rm p}); \quad (1)$$

$$\boldsymbol{E}_{\rm p}^{90} = |\boldsymbol{E}_{\rm p}^{90}|[\boldsymbol{y}^0\cos(\Psi_{\rm p} + 90) + \boldsymbol{z}^0\sin(\Psi_{\rm p} + 90)]$$

or

$$\boldsymbol{E}_{\rm p}^{90} = |\boldsymbol{E}_{\rm p}^{90}|\boldsymbol{e}_{\rm p}^{90} = |\boldsymbol{E}_{\rm p}^{90}|(-\boldsymbol{y}^0\sin\Psi_{\rm p} + \boldsymbol{z}^0\cos\Psi_{\rm p}). \quad (2)$$

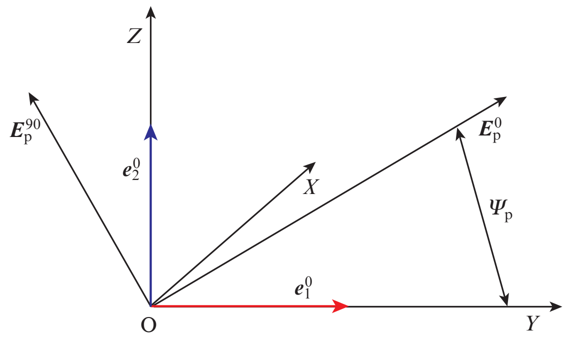

Figure 1. Schematic of a combined pump radiation field directed along the cavity axis, which coincides with the crystallographic X axis.

To control the intensities of the orthogonal components of radiation, we introduce the parameter $\Delta_{\rm p}$ in the form:

$$|\boldsymbol{E}_{\rm p}^0|^2 = |\boldsymbol{E}_{\rm p}|^2\cos^2\Delta_{\rm p},\ |\boldsymbol{E}_{\rm p}^{90}|^2 = |\boldsymbol{E}_{\rm p}|^2\sin^2\Delta_{\rm p}.$$

With a change in $\Delta_{\rm p}$, the intensity of the total pump radiation remains constant:

$$|\boldsymbol{E}_{\rm p}^0|^2 + |\boldsymbol{E}_{\rm p}^{90}|^2 = |\boldsymbol{E}_{\rm p}|^2.$$

At $\Delta_{\rm p} = \pi/4$, the pump radiation becomes circularly polarised. In this case, instead of one set of parameters $\{A_q, b_1, b_2\}$, as in [1], there appear two types A_q^0 and A_q^{90} and two pairs of parameters b_1^0, b_2^0 and b_1^{90}, b_2^{90}. For greater clarity, let us replace the subscripts 1 and 2 with the subscripts π and σ $b_\pi^{0,90} \equiv b_1^{0,90}$ and $b_\sigma^{0,90} \equiv b_2^{0,90}$. Then we have

$$b_{\pi}^{0} = b_{\pi}A^{0} = \frac{\tau_2 T_{\rm a}^{\pi}|\mu_{\rm a}^{\pi}|^2}{\hbar^2}{\rm Re}(L_{\rm a}^{\pi})|E_{\rm p}^{0}|^2,$$
$$b_{\sigma}^{0} = b_{\sigma}A^{0} = \frac{\tau_2 T_{\rm a}^{\sigma}|\mu_{\rm a}^{\sigma\pm}|^2}{\hbar^2}{\rm Re}(L_{\rm a}^{\sigma\pm})|E_{\rm p}^{0}|^2, \quad (3)$$

$$b_{\pi}^{90} = b_{\pi}A^{90} = b_{\pi}|E_{\rm p}^{90}|^2, \; b_{\sigma}^{90} = b_{\sigma}A^{90} = b_{\sigma}|E_{\rm p}^{90}|^2, \quad (4)$$

where $A^{0,90} = |E_{\rm p}^{0,90}|^2$; $A = A^0 + A^{90}$ is the pump parameter;

$$A_q^0 = \frac{b_{\pi}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\pi q}|^2}{b_{\pi}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\pi q}|^2+1} + \frac{1}{2}\left(\frac{b_{\sigma}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\sigma+q}|^2}{b_{\sigma}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\sigma+q}|^2+1} + \frac{b_{\sigma}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\sigma-q}|^2}{b_{\sigma}^0|\boldsymbol{e}_{\rm p}^0\boldsymbol{e}_{\rm a}^{\sigma-q}|^2+1}\right); \quad (5)$$

$$A_q^{90} = \frac{b_{\pi}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\pi q}|^2}{b_{\pi}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\pi q}|^2+1} + \frac{1}{2}\left(\frac{b_{\sigma}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\sigma+q}|^2}{b_{\sigma}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\sigma+q}|^2+1} + \frac{b_{\sigma}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\sigma-q}|^2}{b_{\sigma}^{90}|\boldsymbol{e}_{\rm p}^{90}\boldsymbol{e}_{\rm a}^{\sigma-q}|^2+1}\right). \quad (6)$$

The meaning of all parameters and designations is given in [1].

Thus, the modification of the model of a bipolarised Nd : YAG laser proposed in [1] concerns only the calculation of the pump parameters and does not in any way affect the equations describing the behaviour of the laser. Therefore, one should expect the appearance of an instability similar to that predicted in [1] under the action of partially polarised pumping and the presence of only one absorption channel: either $b_{\pi} \neq 0$, $b_{\sigma} = 0$, or $b_{\pi} = 0$, $b_{\sigma} \neq 0$. This is confirmed by numerical integration of the system of equations (15) from [1], modified for the case of partially polarised pumping (1)–(6). Figure 2a shows the dependences of the intensities of the polarisation modes, the frequencies of relaxation oscillations, and their attenuation decrements with a change in the intensity of the partially polarised pump radiation; the ratio of the intensities of the orthogonally polarised components is

$$\frac{|\boldsymbol{E}_{\rm p}^{90}|^2}{|\boldsymbol{E}_{\rm p}^{0}|^2} = \frac{\sin^2\Delta_{\rm p}}{\cos^2\Delta_{\rm p}} = \frac{\sin^2 10^{\circ}}{\cos^2 10^{\circ}} = 0.025.$$

It can be seen from Fig. 2a that when a certain critical value $A^{\rm cr}$ is reached, an increase in the pumping parameter leads to instability of the stationary regime through the Hopf bifurcation at the relaxation vibration frequency Ω_3: under pumping $A \geqslant A^{\rm cr}$, the decrement δ_3 becomes positive. In this case, small perturbations of the system no longer attenuate and lead to nonstationary generation. Figure 2b shows the same dependences, but with strictly linearly polarised pumping with the participation of both absorption channels [2]. The qualitative similarity between Figs 2a and 2b indicates that the reason for nonstationary generation is the competitive interaction of polarisation modes, regardless of the sources that maintain their generation.

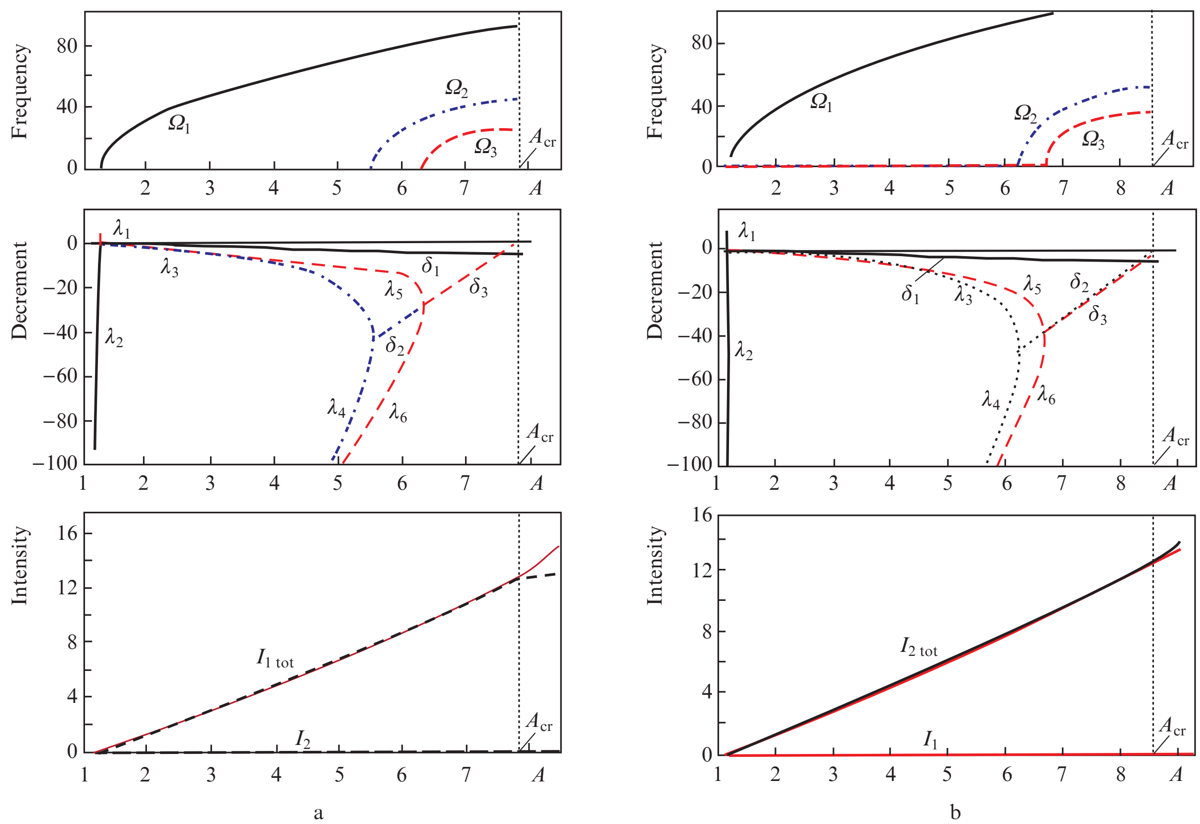

Figure 2. Behaviour of the intensities of laser modes, frequencies and decrements of relaxation oscillations as a function of the pump parameter A (a) with the participation of only one type of absorbing dipoles ($b_{\pi} = 0.002$, $b_{\sigma} = 0$) and (b) with the predominant participation of circularly polarised absorbing dipoles ($b_{\pi} = 0.0001$, $b_{\sigma} = 0.0022$); $G = 1000$, $\Psi_{\rm p} = 0$.

3. Conclusions

Thus, a new type of instability of the dynamic behaviour of a bipolarised Nd:YAG laser with partially polarised pump radiation, providing competitive amplification of polarisation modes, was predicted, and a method for experimental verification of theoretical predictions was proposed, which is technically simpler than that proposed in [1].

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References

1. Milovskii N.D., Khandokhin P.A. *Quantum Electron*., **49** (5) 497 (2019) [*Kvantovaya Elektron*., **49** (5), 497 (2019)].
2. Khandokhin P.A. *Quantum Electron*., **50** (9), 826 (2020) [*Kvantovaya Elektron*., **50** (9), 826 (2020)].
3. Bouwmans G., Segard B., Glorieux P., Milovsky N., Khandokhin P., Shirokov E. *Radiophys. Quantum Electron*., **47** (10-11), 729 (2004) [*Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz*., **47**, 813 (2004)].
4. Ievlev I.V., Khandokhin P.A., Shirokov E.Yu. *Quantum Electron*., **36** (3), 228 (2006) [*Kvantovaya Elektron*., **36** (3), 228 (2006)].
5. Zhang Sha., Tan Y., Zhang Shu. *J. Opt*., **17**, 045703 (2015).