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Two-colour emission in a solid-state laser with a dispersive cavity

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Abstract. The output characteristics of a two-colour Nd^{3+} : YAG laser with a dispersive cavity, emitting at 1.32 and 1.06 μm, are considered. The enlargement of the region of stable two-colour lasing, due to the reduced competition in the case of spatially separated channels, is demonstrated. The influence of the size of the pumped region on the laser efficiency and the competition between the lasing channels is studied. It is shown that, in the case of a single pump source, the weakening of the competition between the waves is accompanied by a reduction in the laser efficiency. A novel construction of the two-channel laser with two pump sources is proposed, which offers increased stability without the reduction in the efficiency.

1. Introduction

Interest in solid-state lasers emitting simultaneously at two wavelengths (we will refer to them as two-colour lasers) is caused by the wide range of their possible practical applications, first of all, the high-precision measurements based on the differential technique [1 – 8], and the technological advantages of the new generation of solid-state lasers with the monochromatic pumping [9]. The practical applications of two-colour lasers require high stability of their output parameters. However, the strong competition between different waves in the active element leads to the amplitude instability of the output radiation. If the losses of one of the lasing channels are modulated, one can observe complex dynamic lasing regimes in these lasers [10].

The possibility of achieving the two-colour lasing at $\lambda_1 = 1.32$ nm and $\lambda_2 = 1.06$ μm in Nd^{3+} : YAG lasers of various designs has already been demonstrated [11 – 15]. However, the high sensitivity of the two-colour lasing to the losses at any of the wavelengths did not allow one to reach the stability comparable to that of single-colour lasers with the monochromatic pumping [9].

In this work, we study both theoretically and experimentally, a two-colour solid-state Nd^{3+} : YAG laser with a dispersive cavity.

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2. Weakening of the competition between the lasing channels. The laser design

Weakening of competition between the lasing channels of the two-colour laser is based on the spatial separation (perpendicularly to the optical axis) of the lasing channels in the active element. This mechanism was earlier used, for example, in two-frequency gas lasers [16], and two-colour dye and colour centre lasers [7].

Fig. 1 shows the optical scheme of the two-colour laser with a dispersive cavity. The geometry of the beam paths illustrates the spatial separation of the lasing channels inside the cavity. Since the beams λ_1 and λ_2 are parallel to each other near the plane mirror, the angle of incidence θ_{in} of these beams on the output surface, cut at the Brewster angle, is the same. It coincides with the internal Brewster angle for the wavelength λ_1, at which the gain is greater than at λ_2. The refraction angles θ_1 and θ_2 of the two output beams are different and defined by the expression $\theta_{1,2} = \arcsin(n_{1,2} \sin\theta_{in})$; the difference between these angles is $\Delta\theta_{1,2} = \arcsin(n_1 \sin\theta_{in}) - \arcsin(n_2 \sin\theta_{in})$. Here, n_1 and n_2 are the refractive indices of the active element at the respective wavelengths.

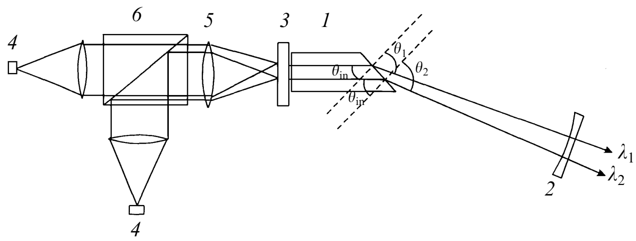

Figure 1. Optical scheme of the two-colour laser with a dispersive cavity: (*1*) active element, (*2*) output spherical mirror, (*3*) input dichroic mirror, (*4*) pump sources, (*5*) focusing system, (*6*) polarising prism.

Thus, in the considered laser, the light beams of different wavelengths (more precisely, their optical axes) are displaced with respect to each other in the perpendicular direction to the plane mirror normal, which leads to their incomplete overlap in the active element. As is known, the reduction in the spatial overlap between the lasing channels in a two-channel laser stabilises the two-channel lasing regime [7, 14 – 16].

3. The theoretical model

We will consider the two-colour generation in a laser with the dispersive cavity and the longitudinal monochromatic pumping using the following approximations:

The radiation at each of the two wavelengths uniformly occupies the cavity in the longitudinal direction. (This condition is always satisfied in travelling-wave lasers and linear lasers in the multimode regime with respect to the longitudinal index);

the spatial distribution of the radiation field in the lasing channels coincides with the spatial distribution of the fundamental (or another) mode of the empty cavity at the corresponding wavelength, i.e., the mode deformation is neglected. (This condition is fairly well satisfied in the considered lasers with the continuous monochromatic pumping in the case of a small active medium gain);

the combination nonlinear interaction between the two channels is negligible;

the both lasing channels employ a four-level scheme with a negligible lifetime of the lower working level.

If these conditions are satisfied, each channel can be characterised by a single variable describing the channel as a whole. For example, we can use the total number of photons in each channel $\Phi_{\rm i}$, where $i = 1, 2$. In this case, the distribution of the photon density over the channel is given by

$$\phi_i(\boldsymbol{r}) = \frac{\Phi_i |U_i(\boldsymbol{r})|^2}{\int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V}, \qquad (1)$$

where $|U_i(\boldsymbol{r})|$ is a known function describing the amplitude of the i-th mode of the empty cavity, and V is the cavity volume.

The equation for the total number of photons in the mode has the form

$$\frac{\mathrm{d}\Phi_i}{\mathrm{d}t} = -\frac{\Phi_i}{\tau_\phi} + \int_V \Delta N_i(\boldsymbol{r}) D_i \frac{\Phi_i |U_i(\boldsymbol{r})|^2}{\int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V} \mathrm{d}V, \qquad (2)$$

where $\Delta N_i(\boldsymbol{r})$ is population inversion density in the i-th channel; $D_i = c\sigma_i^{\rm int}/n_i$; $\sigma_i^{\rm int}$ is the cross section of the interaction with radiation of the i-th channel; c is the speed of light in vacuum; n_i is the refractive index of the medium at the wavelength of the i-th channel; and τ_ϕ is the lifetime of the radiation in the empty cavity.

The equation for the population inversion density can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta N_{1,2}(\boldsymbol{r}) = R_{\rm pump}(\boldsymbol{r}) - \frac{\Delta N_{1,2}(\boldsymbol{r})}{T_1} - D_{1,2}\Delta N_0(\boldsymbol{r})$$

$$\times \frac{\Phi_{1,2} |U_{1,2}(\boldsymbol{r})|^2}{\int_V |U_{1,2}(\boldsymbol{r})|^2 \mathrm{d}V} - D_{2,1}\Delta N_0(\boldsymbol{r}) \frac{\Phi_{2,1} |U_{2,1}(\boldsymbol{r})|^2}{\int_V |U_{2,1}(\boldsymbol{r})|^2 \mathrm{d}V}, \qquad (3)$$

where T_1 is the relaxation time of the population inversion;

$$R_{\rm pump}(\boldsymbol{r}) = W_{\rm pump} \frac{|U_{\rm pump}(\boldsymbol{r})|^2}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V}$$

is the pumping rate; $W_{\rm pump}$ is the average pumping rate; $U_{\rm pump}(\boldsymbol{r})$ is a known function describing the spatial distribution of the pumping field amplitude; and

$$\Delta N_0(\boldsymbol{r}) = R_{\rm pump}(\boldsymbol{r}) T_1 = W_{\rm pump} T_1 \frac{|U_{\rm pump}(\boldsymbol{r})|^2}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V} \qquad (4)$$

is the stationary population inversion density. We introduce the amplification increment (gain)

$$W_i^{\rm for} = D_i \frac{\int_V \Delta N_i(\boldsymbol{r}) |U_i(\boldsymbol{r})|^2 \mathrm{d}V}{\int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V}$$

and recast equation (2) in the form

$$\frac{\mathrm{d}\Phi_i}{\mathrm{d}t} = -\frac{\Phi_i}{\tau_\phi} + \Phi_i W_i^{\rm for}. \qquad (5)$$

By multiplying the both sides of Eqn. (3) by $D_i \times |U_i(\boldsymbol{r})|^2 / \int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V$ and substituting expression (4) into the result, assuming that the excess of the pump over the threshold value is not large and integrating over the cavity volume, we obtain the following equation for the gain

$$\frac{\mathrm{d}W_i^{\rm for}}{\mathrm{d}t} = W_{\rm pump} D_i \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^2 \mathrm{d}V}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V \int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V} - \frac{W_i^{\rm for}}{T_1}$$

$$- W_{\rm pump} D_i^2 T_1 \Phi_i \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^4 \mathrm{d}V}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V \left[\int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V\right]^2}$$

$$- W_{\rm pump} D_i D_j T_1 \Phi_j \qquad (6)$$

$$\times \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^2 |U_j(\boldsymbol{r})|^2 \mathrm{d}V}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V \int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V \int_V |U_j(\boldsymbol{r})|^2 \mathrm{d}V}.$$

Let us introduce the following normalised (dimensionless) variables: time $\tau = t/T_1$; the output power

$$I_i = \Phi_i/\Phi_0,$$

where

$$\Phi_0 = \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^2 \mathrm{d}V}{T_1 D_i};$$

the gain $m_i = \tau_\phi W_i^{\rm for}$; the parameter $G = T_1/\tau_\phi$; the pumping rate

$$\alpha_i = T_1 \tau_\phi W_{\rm pump} \frac{D_i}{V_i^{\rm dif}},$$

where

$$V_i^{\rm dif} = \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 \mathrm{d}V \int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V}{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^2 \mathrm{d}V};$$

and the coefficients of self- and cross-saturation

$$\xi_{ii} = \frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^4 {\rm d}V}{\int_V |U_i(\boldsymbol{r})|^2 {\rm d}V},$$

$$\xi_{ij} = \frac{D_j}{D_i}\frac{\int_V |U_{\rm pump}(\boldsymbol{r})|^2 |U_i(\boldsymbol{r})|^2 |U_j(\boldsymbol{r})|^2 {\rm d}V}{\int_V |U_j(\boldsymbol{r})|^2 {\rm d}V},$$

respectively.

In the new notation, equations (5) and (6) reduce to the well-known system of normalised equations

$$\frac{{\rm d}I_i}{{\rm d}\tau} = (m_i - 1)I_i G,$$
$$\frac{{\rm d}m_i}{{\rm d}\tau} = \alpha_i - m_i(1 + \xi_{ii}I_i + \xi_{ij}I_j). \qquad (7)$$

The stationary solutions of system (7) are well known and have the form

$$m_i = 1, \quad I_i = \frac{\xi_{jj}(\alpha_i - 1) - \xi_{ij}((\alpha_j - 1)}{\xi_{ii}\xi_{jj} - \xi_{ij}\xi_{ji}}. \qquad (8)$$

The establishment of the two-channel lasing and its stability, is strongly affected by the self-saturation and cross-saturation of the active element channels. These effects are described by the coefficients ξ_{ii} and ξ_{ij}, respectively. The two-channel lasing becomes more stable when the competition between the channels is reduced owing to a reduction in the cross-saturation coefficients ξ_{ij}.

One of the ways to weaken the competition between the channels in the considered laser (Fig. 1) is to reduce the spatial overlap between the channels in the active element. One can vary this overlap by shifting the spherical mirror with respect to the active element. The closer it is to the active element, the greater is the spatial separation between the channels and the lower is the competition between them. Fig. 2 shows the dependence of the cross-saturation coefficients on the separation between the lasing channels for several pump spot diameters. One can see that an increase in the cavity length reduces the cross-saturation coefficients.

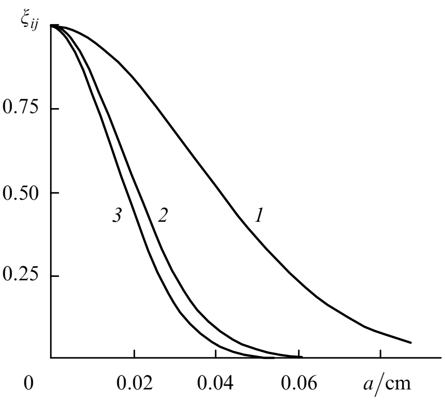

Figure 2. Dependences of the cross-saturation coefficients ξ_{ij} on the distance a between the lasing channels for the pump beam diameters $w_{\rm p} = 1$ 0.01 (*1*), 0.03 (*2*), and 0.06 cm (*3*). The pumping is symmetric with respect to the two lasing channels.

Fig. 3 shows the dependences of the self- and cross-saturation coefficients on the pump spot diameter for $w_{1,2} =$ 0.3 mm and $a = 0.11$ mm, where $w_{1,2}$ are the diameters of the two lasing modes and a is the separation between the lasing channels. The curves shown in Fig. 3 correspond to the symmetric positioning of the pump beam with respect to the two lasing channels.

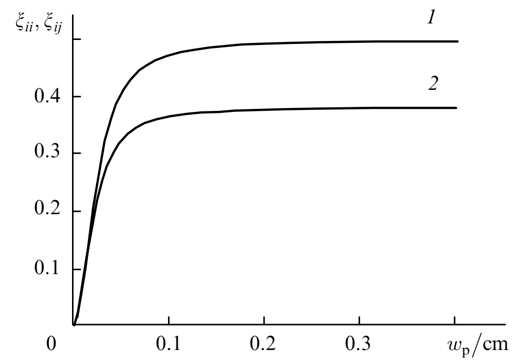

Figure 3. Dependences of the self-saturation coefficients (*1*) and the cross-saturation coefficients (*2*) on the pump spot diameter for $w_{1,2} = 0.3$ mm and $a = 0.11$ mm. The pumping is symmetric with respect to the two lasing channels.

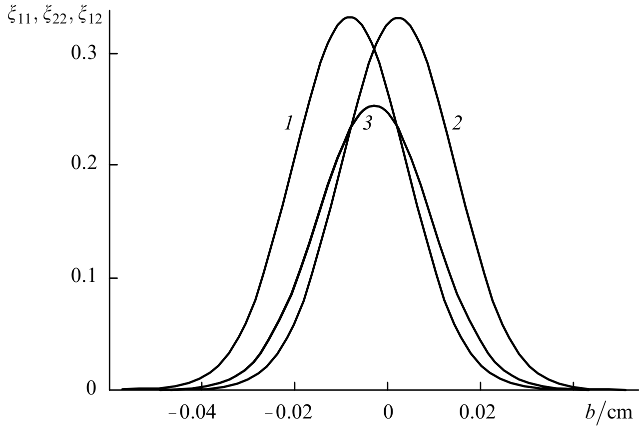

Figure 4. Dependences of the self-saturation coefficients ξ_{11} (*1*), ξ_{22} (*2*) and the cross-saturation coefficient ξ_{12} (*3*) on the displacement b of the pump beam in the perpendicular direction to the optical axis.

A displacement of the pump beam from the symmetric position leads to a variation in the coefficients of self- and cross-saturation and the parameters α_i. Fig. 4 shows the dependence of ξ_{ii} and ξ_{ij} on the displacement of the pump spot from the central position.

We calculated the normalised power of the lasing channels using formula (8) and the expressions for α_i, ξ_{ii} and ξ_{ij}, assuming that there is no lasing at the higher order modes. Fig. 5 shows the dependences of the output power of each of the two channels on the displacement of the pump spot from the symmetric position.

Our analysis has shown that, in order to increase the stability of the two-channel lasing, one has to increase the size of the pumped volume. However, an increase in the pump spot diameter reduces the efficiency of the conversion of the pump to the output laser power. For these reasons, we propose a novel scheme that allows one to reduce the overlap coefficients without losing the high lasing efficiency. A sec-

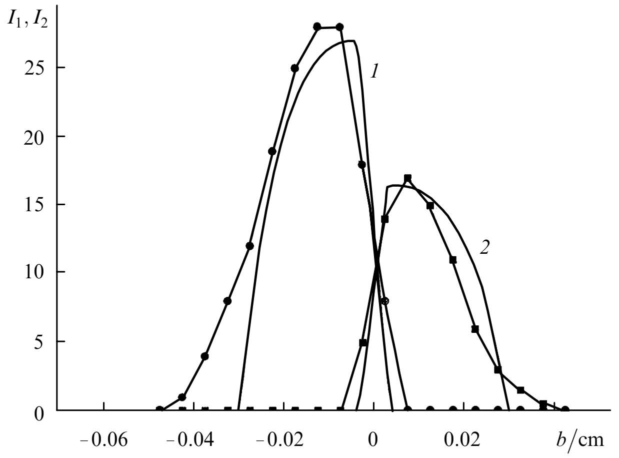

Figure 5. Theoretical (solid curves) and experimental (dots) dependences of the normalised powers of the first (1, ●) and the second (2, ■) lasing channels on the displacement b of the pump beam in the perpendicular direction to the optical axis. The parameters are $w_p = 0.03$ cm and $a = 0.011$ cm.

ond pump laser is used in this scheme so that one of the pump beams is focused on the waist of the first lasing channel and the other, on the waist of the second (see Fig. 1).

The coefficients of self- and cross-saturation are then determined by the relationships

$$\xi_{ii} = \frac{\int_V \left(|U_{1\text{pump}}(\boldsymbol{r})|^2 + |U_{2\text{pump}}(\boldsymbol{r})|^2\right)|U_i(\boldsymbol{r})|^4 \mathrm{d}V}{\int_V |U_i(\boldsymbol{r})|^2 \mathrm{d}V},$$

$$\xi_{ij} = \frac{D_j}{D_i}\,\frac{\int_V \left(|U_{1\text{pump}}(\boldsymbol{r})|^2 + |U_{2\text{pump}}(\boldsymbol{r})|^2\right)|U_i(\boldsymbol{r})|^2 |U_j(\boldsymbol{r})|^2 \mathrm{d}V}{\int_V |U_j(\boldsymbol{r})|^2 \mathrm{d}V}.$$

In this scheme, the pumping is realised by two lasers with orthogonal planes of polarisation, whose radiation is mixed by a polarisation mixer.

4. Comparison between the theory and experiment

We compared the theoretical conclusions with the results of an experimental study of a laser with a dispersive cavity and the monochromatic pump.

In the optical scheme of the experimental setup (Fig. 1), the active element *1* was cut at the Brewster angle for $\lambda_1 = 1.32$ μm. The output spherical mirror *2* with a radius of curvature of 200 mm had the reflectivities $R_1 = 97\%$ and $R_2 = 82\%$ at $\lambda_1 = 1.32$ μm and $\lambda_2 = 1.06$ μm, respectively. The dichroic mirror *3* had a very high reflectivity (99%) at the both lasing wavelengths and the transmittance $T = 92\%$ at the pump wavelength.

An argon laser served as the pumping source. An interference filter selected the 0.5145-μm line lying within the absorption band of Nd^{3+} ions. The maximum power of the pump beam behind the interference filter was ~ 1.5 W. The lens *5* ($F = 180$ mm) focused the argon-laser beam on the front end of the active element *1*. The lasing parameters were controlled by varying the temperature of the Nd^{3+} : YAG crystal in a thermostat and by moving the active element perpendicular to the pump beam along the spatial separation between the generated waves. The output powers of the beams at λ_1 and λ_2 were monitored by a wideband photodiode (at λ_2), a photoresistor (at λ_1), and a multichannel oscillograph. An IMO-2 power meter measured the average powers of the two beams.

Our experiments have shown that the optimal positioning of the active element makes possible continuous simultaneous lasing at the both wavelengths λ_1 and λ_2 in the pumping power range 300 mW $< P <$ 1500 mW and at room temperature, without using the temperature adjustment. The output powers of the generated waves (in the two-wave regime) can be efficiently controlled by moving the pump spot over the front end of the active element. The experimental dependences of the output on the displacement of the pump region is shown by dots in Fig. 5. One can see a good agreement between the experimental and theoretical results.

The enlargement of the region of stable two-colour lasing with increasing pump spot was also confirmed experimentally. However, the accompanying reduction in the efficiency of the two-colour laser makes this method impractical for stabilisation of the two-colour lasing. We conducted a model experiment to verify the effectiveness of the proposed scheme of the two-wave laser pumped by two independent diode lasers with optimal dimensions of the pumped regions (Fig. 1). The radiation of the two independent diode lasers was modeled by an argon laser. A beamsplitter containing a polarising prism was installed at its output. It divided the output beam into two beams with mutually orthogonal polarisation and equal powers. These beams were then recombined in polarisation cube *6* and focused by optical system *5* on active element *1*.

Upon two-beam pumping, the lasing efficiency increased considerably (more than by factor of 4) while the relative instability of the output power at λ_1 decreased to 0.003 in the frequency range from 10 Hz to 1 kHz. The achieved efficiency of the two-colour laser is virtually equal to that of a single-colour laser emitting at λ_1.

5. Conclusions

Thus, the spatial separation of lasing channels in the active element by means of a dispersive cavity is an efficient way to reduce the competition between the channels, enlarge the region of two-colour lasing, and increase its stability. However, in the case of a single pump source, one cannot reduce the competition between the channels without simultaneously decreasing the laser efficiency.

The laser design with two independently tunable pump light beams proposed in this work allows one to substantially decrease the competition between the lasing channels without reducing the efficiency of the two-colour laser.

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