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Dependence of polarisation of radiation of a linear Nd : YAG laser on the pump radiation polarisation

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***Abstract*. The dependence of polarisation characteristics of radiation of a linear Nd : YAG laser on polarisation of radiation of a pump diode laser is studied experimentally and theoretically. It is shown that, in the case of polarisation isotropy of the optical resonator, the polarisation of radiation of the Nd : YAG laser is completely determined by the polarisation of pump radiation. Based on the vector model of this laser pumped by polarised radiation, an analytic solution describing stationary lasing is obtained.**

Keywords: *Nd : YAG laser, polarisation effects, vector lasers, Faraday effect, diode laser pumping.*

1. Introduction

Broad applications of lasers in science and technology stimulate interest in the development of efficient methods for controlling all the parameters of laser radiation, in particular, its polarisation. The study of polarisation of radiation of a Nd : YAG laser as a function of the pump polarisation is also of interest for analysis of the properties of the so-called vector lasers with a weak polarisation anisotropy of the resonator, in which polarisation of radiation is not fixed but depends on many parameters. A specific feature of such lasers is the dependence of their dynamics on polarisation degrees of freedom.

It was shown in many experimental and theoretical papers that polarisation of radiation of diode-pumped Nd : YAG lasers depends on the pump polarisation, and in the case of an anisotropic resonator, the lasing dynamics and polarisation characteristics of output radiation can be controlled by varying the pump polarisation [1 – 10]. However, an important limiting case of a polarisation-isotropic resonator was not analysed in these papers. In addition, the authors of theoretical papers based on the vector model of a Nd : YAG laser performed only numerical studies of the polarisation characteristics and radiation dynamics.

In this paper, we studied experimentally the polarisation characteristics of the output radiation (the degree of ellipticity and polarisation azimuth) of a Nd : YAG laser with a polarisation-isotropic resonator as a function of the pump polarisation and showed analytically that polarisation of radiation in such a laser coincides with the pump polarisation.

2. Experimental

Figure 1 shows the scheme of the experimental setup. We studied the dependence of polarisation of radiation from a longitudinally diode-pumped linear Nd : YAG laser on the ellipticity and orientation of the polarisation plane of pump linearly polarised radiation from a diode laser.

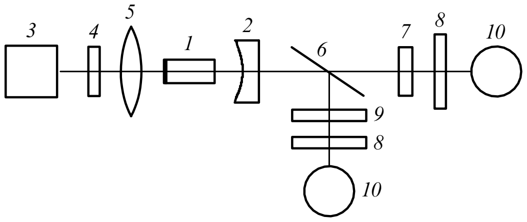

Figure 1. Scheme of the experimental setup: (*1*) active element; (*2*) spherical mirror; (*3*) pump diode laser; (*4*) device rotating the polarisation plane or changing polarisation ellipticity; (*5*) focusing lens; (*6*) beamsplitter; (*7*) analysers; (*8*) 1.064-μm optical filters; (*9*) 0.81-μm optical filter; (*10*) photodetectors.

The active element of the laser was a rod of diameter 3.5 mm and length 15 mm cut from a high-quality $Nd^{3+} : Y_3Al_5O_{12}$ single crystal. On the input end of the rod, a selective mirror was deposited which had the high reflectivity (above 99 %) at the laser wavelength 1.064 μm and a relatively high transmission (~ 90 %) at the pump wavelength 0.81 μm. The output end of the rod was covered with an antireflection coating. The linear resonator of the laser of length ~ 18 mm was formed by a selective mirror deposited on the input end of the rod and by the output spherical mirror with the radius of curvature 1000 mm and the reflectivity ~ 98 % at 1.064 μm. Lasing was produced at the fundamental transverse TM_{00q} mode.

We devoted special attention to providing the polarisation isotropy of the resonator. The matter is that even a pump beam with the noncircular spatial profile (radiation of a diode laser has different divergence in the vertical and horizontal planes) could induce birefringence and polarisation anisotropy in the active element due to its local heating. The polarisation isotropy of the resonator in our

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experiments was achieved by using a high-quality garnet crystal, in which the most homogeneous region was selected, and by accurately adjusting the resonator for the specified spatial profile of the pump radiation distribution and fixed pump power.

The polarisation plane of the pump radiation was rotated and the polarisation ellipticity was changed by means of a device placed between the diode laser and the Nd : YAG laser. This device could be a Faraday rotator, a phase half-wave plate or quartz plates with a fixed phase shift allowing one to change the polarisation ellipticity. The output radiation of the Nd : YAG laser and a transmitted part of the pump radiation (about 1 % of the pump power) passed through analysers (Nicol prisms) and appropriate filters and were incident on two photodetectors whose signals were recorded with a two-beam digital oscilloscope. Polarisations of the output laser radiation and a part of the pump radiation transmitted through the laser were determined by rotating Nicol prisms. The accuracy of measurement of the polarisation azimuth was ±1°.

3. Experimental results

Our study has shown that polarisation of radiation of a Nd : YAG laser with a polarisation-isotropic resonator is determined by polarisation of radiation of a pump diode laser. When the pump radiation is linearly polarised, the output radiation of the Nd : YAG laser is also linearly polarised and its polarisation plane coincides with that of the pump radiation. The rotation of the polarisation plane of pump radiation through a certain angle leads to almost the same rotation of the polarisation plane of laser radiation. Figure 2 shows the experimental dependence of the rotation angle of the polarisation plane of the output radiation for the Nd : YAG laser on the rotation angle of the polarisation plane of linearly polarised pump radiation. One can see that this dependence is linear.

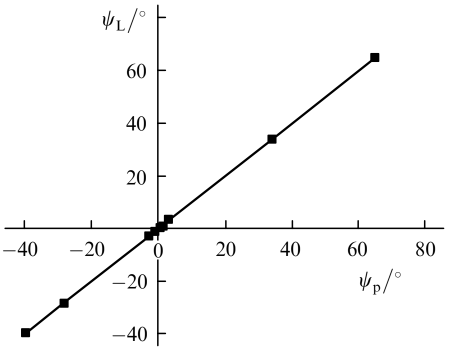

Figure 2. Dependence of the rotation angle of the polarisation plane of output laser radiation on the rotation angle of the polarisation plane of pump radiation.

Note that, in the case of linearly polarised pump radiation, the output laser radiation remains also linearly polarised when the lasing threshold is exceeded more than twice, when several longitudinal modes are simultaneously generated. The presence of linear polarisation was controlled by a complete 'quenching' of a signal during the rotation of an analyser.

When the pump radiation was circularly (or elliptically) polarised, the radiation of the Nd : YAG laser had the same circular (or elliptical) polarisation, the degree of ellipticity and polarisation azimuths of these radiations being almost coincident.

4. Theoretical analysis

Our experimental results can be explained with the help of the vector model of a single-mode Nd : YAG laser proposed in [3]. This model describes the field inside the resonator by two orthogonal components determined by the unit polarisation vectors $\boldsymbol{e}_x$ and $\boldsymbol{e}_y$:

$$E(t) = \mathrm{Re}\{E_x \exp[-\mathrm{i}(\omega_x t + \varphi_x)]\boldsymbol{e}_x$$
$$+ E_y \exp[-\mathrm{i}(\omega_y t + \varphi_y)]\boldsymbol{e}_y\}, \quad (1)$$

where $E_{x,y}$ and $\varphi_{x,y}$ are the amplitudes and phases of the polarisation components; $\omega_{x,y}$ are the eigenfrequencies of the resonator determining its phase anisotropy. Consider a Nd : YAG laser longitudinally pumped along the z axis. The model neglects in the first approximation the spatial inhomogeneity of the population inversion both in the longitudinal and transverse directions and assumes that the distribution of the dipole moments of the active Nd ions is isotropic. During saturation of the inverse population by polarised laser radiation, the angular inhomogeneity in the distribution of the inverse population appears. In this case, the inverse population can be described by the function $D(\theta, t)$ depending on the angle θ between the directions of the dipole moment and the x axis. Unlike [3], we assume that pumping is linearly polarised. The pump rate in the equation for the inverse population $D(\theta, t)$ [see (6) in [3]] can be written in the form

$$P = 2A_0 \cos^2(\theta - \psi_{\mathrm{p}}), \quad (2)$$

where A_0 is the coefficient depending on the pump intensity and the square of the modulus of the dipole-transition matrix element corresponding to absorption of pump radiation, and ψ_{p} is the angle determining the orientation of the pump polarisation with respect to the x axis.

By expanding the angular distribution of the inverse population $D(\theta, t)$ in a Fourier series, taking only the three first Fourier components into account

$$D_0 = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\theta D(\theta, t), \quad D_1 = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\theta \cos 2\theta D(\theta, t),$$
$$D_2 = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\theta \sin 2\theta D(\theta, t)$$

we can describe the dynamics of the Nd : YAG laser by the system of differential equations [3]

$$\frac{\mathrm{d}I_x}{\mathrm{d}t} = -\Gamma_x I_x + \Delta\omega_{\mathrm{L}}(I_x I_y)^{1/2}\cos\Psi + 2\alpha_x(D_0 + D_1)I_x$$
$$+ 2(\alpha_x \cos\Psi + \tilde{\alpha}_x \sin\Psi)D_2(I_x I_y)^{1/2},$$

$$\frac{\mathrm{d}I_y}{\mathrm{d}t} = -\Gamma_y I_y + \Delta\omega_{\mathrm{L}}(I_x I_y)^{1/2}\cos\Psi + 2\alpha_{yx}(D_0 - D_1)I_y +$$

$$+2(\alpha_y\cos\Psi-\tilde{\alpha}_y\sin\Psi)D_2(I_xI_y)^{1/2},$$

$$\begin{aligned}\frac{\mathrm{d}\Psi}{\mathrm{d}t}&=\omega_x-\omega_y-\Delta\omega_{\mathrm{d}}\left\{\left[\left(\frac{I_x}{I_y}\right)^{1/2}+\left(\frac{I_y}{I_x}\right)^{1/2}\right]\sin\frac{\Psi}{2}\right.\\&\left.+(\alpha_y\sin\Psi+\tilde{\alpha}_y\cos\Psi)\left(\frac{I_x}{I_y}\right)^{1/2}\right\}D_2+\tilde{\alpha}_x(D_0+D_1)\\&-\tilde{\alpha}_y(D_0-D_1)-\left[(\alpha_x\sin\Psi-\tilde{\alpha}_x\cos\Psi)\left(\frac{I_y}{I_x}\right)^{1/2}\right],\end{aligned}\tag{3}$$

$$\begin{aligned}\frac{\mathrm{d}D_0}{\mathrm{d}t}&=\gamma(P_0-D_0)-\alpha_x\gamma(D_0+D_1)I_x-\alpha_y\gamma(D_0-D_1)I_y\\&-[(\alpha_x+\alpha_y)\cos\Psi+(\tilde{\alpha}_x-\tilde{\alpha}_y)\sin\Psi]\gamma D_2(I_xI_y)^{1/2},\end{aligned}$$

$$\frac{\mathrm{d}D_1}{\mathrm{d}t}=\gamma(P_1-D_1)-\alpha_x\gamma\left(\frac{D_0}{2}+D_1\right)I_x-\alpha_y\gamma\left(D_1-\frac{D_0}{2}\right)I_y,$$

$$\begin{aligned}\frac{\mathrm{d}D_2}{\mathrm{d}t}&=\gamma(P_2-D_2)-\alpha_x\gamma D_2I_x-\alpha_y\gamma D_2I_y\\&-[(\alpha_x+\alpha_y)\cos\Psi+(\tilde{\alpha}_x-\tilde{\alpha}_y)\sin\Psi]\frac{\gamma D_0(I_xI_y)^{1/2}}{2},\end{aligned}$$

where the parameters P_0, P_1, and P_2 determine the pump rate in equations for the corresponding Fourier components of the inverse population and are described by the expressions

$$\begin{aligned}P_0&=\frac{1}{2\pi}\int_0^{2\pi}P(\theta)\mathrm{d}\theta=A_0,\\P_1&=\frac{1}{2\pi}\int_0^{2\pi}P(\theta)\cos2\theta\,\mathrm{d}\theta=\frac{1}{2}A_0\cos2\psi_{\mathrm{p}},\\P_2&=\frac{1}{2\pi}\int_0^{2\pi}P(\theta)\sin2\theta\,\mathrm{d}\theta=\frac{1}{2}A_0\sin2\psi_{\mathrm{p}}.\end{aligned}\tag{4}$$

In the system of equations (3), $I_{x,y}=aE_{x,y}^2$ are the relative intensities of polarisation components; a is the saturation parameter; $\Psi=(\omega_x-\omega_y)t+\varphi_x-\varphi_y$; $\Gamma_{x,y}$ are the widths of the resonator bands (their difference determines the amplitude anisotropy of the resonator); γ is the relaxation rate of the population inversion. The coefficients $\alpha_j=1/[1+T_{\mathrm{s}}^2(\omega-\omega_j)^2]$ and $\tilde{\alpha}_j=T_{\mathrm{s}}(\omega-\omega_j)\alpha$ $(j=x,\ y)$ take into account the effect of relative detunings of the resonator eigenfrequencies $\omega_{x,y}$ from the gain line centre; and T_{s} is the relaxation time of the polarisation vector of the medium. The parameter $\Delta\omega_{\mathrm{L}}$ characterises the linear coupling of polarisation components in the resonator, which results in frequency locking.

Consider the case of a polarisation-isotropic resonator, when $\Gamma_x=\Gamma_y=\Gamma$, $\omega_x-\omega_y=0$, and $\Delta\omega_{\mathrm{L}}=0$. We assume that the radiation frequency coincides with the centre of the gain line. In this case, the coefficients α_j and $\tilde{\alpha}_j$ take the values $\alpha_x=\alpha_y=1$, $\tilde{\alpha}_x=\tilde{\alpha}_y=0$.

Analysis of the system of equations (3) shows that in the absence of polarisation anisotropy of the resonator, a stationary solution with polarisation of the output radiation coinciding with the pump polarisation is only possible. In this case, the intensity of polarisation components has the form

$$I_x=I_0\cos^2\psi_{\mathrm{p}},\quad I_y=I_0\sin^2\psi_{\mathrm{p}},\tag{5}$$

where I_0 is the total intensity. It follows from the equation for the phase difference Ψ in system (3) that $\Psi=0$. In this case, the amplitudes of spatial harmonics of the inverse population take the form

$$D_1=D_1^0\cos2\psi_{\mathrm{p}},\quad D_2=D_2^0\sin2\psi_{\mathrm{p}}.\tag{6}$$

The system of equations in the stationary case can be reduced to the form

$$\begin{aligned}&\Gamma=2\big(D_0+D_1^0\big),\\&A_0-D_0-\big(D_0+D_1^0\big)I_0=0,\\&\frac{1}{2}A_0-D_1^0-\left(D_1^0+\frac{1}{2}D_0\right)I_0=0,\\&\frac{1}{2}A_0-D_2^0-\left(D_2^0+\frac{1}{2}D_0\right)I_0=0.\end{aligned}\tag{7}$$

The solution of this system is described by the expressions

$$\begin{aligned}I_0&=\frac{1}{2}\left(\frac{3}{\Gamma_x}A_0-1\right),\\D_0&=A_0\left(1+\frac{3}{2}I_0+\frac{1}{2}I_0^2\right)[(1+I_0)(1+2I_0)]^{-1},\\D_1^0&=D_2^0=A_0\,\frac{1-I_0}{2(1+2I_0)}.\end{aligned}\tag{8}$$

One can see from (8) that the output radiation intensity linearly depends on the pump power. However, the character of saturation of the population inversion proves to be quite complicated: one can see from (8) that the homogeneous component D_0 of the inverse population and its spatial harmonics are saturated by the intracavity field differently, which leads to changes in the frequency and the decay decrement of relaxation oscillations. We plan to study this question in detail elsewhere.

Note that we used in the theoretical analysis the vector model for a Nd : $Y_3Al_5O_{12}$ laser which assumes that the distribution of the dipole moments of active centres is isotropic. However, actually the active Nd^{3+} ions substitute yttrium ions with the local symmetry D_2 in the cubic $Y_3Al_5O_{12}$ crystal matrix. As a result, the local electric field of compensating charges should cause the anisotropy of absorption of pump radiation and of amplification of radiation at the lasing wavelength of the Nd^{3+} ions [1]. However, our study has shown that, despite this fact, polarisation of the output radiation of the Nd : YAG laser with the polarisation-isotropic resonator is almost completely determined by polarisation of pump radiation. This can be caused by a relatively weak polarisation anisotropy of Nd^{3+} : YAG crystals, so that its consideration can only lead to a small difference in the orientation of the polarisation plane of laser radiation from that for pump radiation. Numerical simulations performed in [2] also confirm such a possibility.

5. Conclusions

We have studied experimentally and analytically the effect of the pump polarisation on the polarisation characteristics of a linear Nd : YAG laser with a polarisation-isotropic resonator and have found that polarisation of radiation of the Nd : YAG laser is almost completely determined by polarisation of pump radiation. The experimental and theoretical results are in good qualitative agreement. The experimental results have been explained using the vector model of the laser [3] taking the pump polarisation into account.

The results obtained in the paper can be useful in laser technologies. The dependence of polarisation of output laser radiation on the pump polarisation can be used, for example, to enhance the efficiency of the polarisation magneto-optical or electro-optical control of radiation of IR lasers. Indeed, the efficiency of electro-optical and magneto-optical modulators based on the electro-optical Pockels and Kerr effects and the magneto-optical Faraday effect is much lower in the IR region than in the visible region. Therefore, the method for controlling polarisation of output laser radiation considered above proves to be more efficient compared to the conventional method.

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