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Investigation of diode-pump absorption efficiency and thermo-optical effects in a high-power Yb : KGW laser

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Abstract. **Diode-pump absorption is experimentally studied in a high-power Yb : KGd(WO$_4$)$_2$ (Yb : KGW) laser in the presence and absence of lasing. The maximum absorption efficiency in the cw regime exceeds 77 % which is by a factor of 1.4 greater than the maximum absorption efficiency in the absence of lasing. The powers of thermo-optical lenses induced in laser crystals during lasing are measured. A strong dependence of the lens power and aberrations on the orientation of laser crystals relative to the propagation direction and polarisation is confirmed.**

Keywords: *solid-state laser, Yb : KGW, optical pumping, pump power, laser diodes, absorption, output power.*

1. Introduction

A considerable progress has been observed in the development of high-power solid-state laser sources in the near-IR spectral range $\lambda \approx 1$ μm. Ytterbium-doped crystals have been recognised as very attractive active media for such lasers because they can be pumped by high-power and relatively inexpensive InGaAs laser diodes at a wavelength of ~980 nm and have a relatively low quantum defect, which may noticeably reduce the heat release and, hence, thermo-optical effects. These effects, as is known [1, 2], strongly affect the parameters of generated or amplified laser radiation. Ytterbium-doped active media also have a substantially wider gain band than, for example, neodymium-doped media, which allows one to employ them for generating and amplifying femtosecond laser pulses [3 – 5].

As ytterbium-doped crystals one may mention double potassium gadolinium tungstates, Yb : KGd(WO$_4$)$_2$ (Yb : KGW) and Yb : KY(WO$_4$)$_2$ (Yb : KYW) [6], that have substantially greater cross sections of absorption ($\sim 1.2\times10^{-19}$ cm^2) and stimulated emission ($\sim 1.2 - 2\times10^{-20}$ cm^2) as compared to other crystal media, which facilitates their optical pumping and amplification of stimulated emission. A relatively high thermal conductivity (~2.5 – 3.5 W m^{-1} K^{-1}) allows one to generate or amplify radiation with a high average power (dozens of watts) with self-suppression of depolarisation related to the biaxial crystal anisotropy. The width of the absorption spectrum at 981 nm (~3.5 nm) is sufficient for efficient pumping by commercial laser diodes, and the gain width (~15 nm) provides generation and amplification of pulses with a duration of shorter than 200 fs [7 – 9].

However, the quasi-three-level character of the active medium and the dependence of spectral characteristics of laser diodes on temperature result in the dependence of absorption efficiency on the pump power and lasing power. Anisotropy of thermo-optical and thermo-mechanical parameters of crystals leads to strong thermo-optical aberrations [10, 11]. All these factors in Yb : KGW crystals yield a sufficiently complicated dependence of the output power and brightness of laser radiation on the pump power [12, 13], which can hardly be calculated by analytical or numerical methods.

In the present work we present results of a thorough experimental study of pump absorption and thermo-optical lens power in Yb : KGW crystals at high powers of laser diodes.

2. Absorption of pump radiation and amplification in Yb : KGW crystals

In three-level laser media, in contrast to four-level media, the active element absorbs radiation at the laser wavelength in the absence of pumping. There exists the minimal pump intensity (transparency intensity) at which the active medium is bleached and a lasing threshold is attained [5]:

$$I_{\min}(\lambda_{\rm las},\lambda_{\rm p}) = hc\left(\lambda_{\rm p}\left[\sigma_{\rm abs}(\lambda_{\rm p})\frac{\sigma_{\rm em}(\lambda_{\rm las})}{\sigma_{\rm abs}(\lambda_{\rm las})} - \sigma_{\rm em}(\lambda_{\rm p})\right]\tau\right)^{-1}, \quad (1)$$

where $\lambda_{\rm p}, \lambda_{\rm las}$ are the wavelengths of pump and laser radiation, respectively; $\sigma_{\rm abs}$, $\sigma_{\rm em}$ are the absorption and stimulated emission cross sections; and τ is the lifetime of the upper laser level.

For Yb : KGW crystals we have $I_{\min} \approx 4$ kW cm^{-2}, which is several times less than, for example, for a popular Yb : YAG crystal; therefore, the pump conditions are easier. Nevertheless, even a Yb : KGW crystal requires high-power assemblies of laser diodes in the form of stacks or bars capable of concentrating radiation in a sufficiently small volume. For the same reason, quasi-three-level active media are usually used with end pumping, which facilitates concentration of radiation of laser diodes.

Because absorption and generation bands have close centre wavelengths and are sufficiently wide, in most ytterbium media laser radiation is reabsorbed, which complicates the lasing dynamics and affects laser parameters. Laser parame-

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ters are usually calculated by using balance equations for the population of laser levels [1, 2, 5, 14]. For ideal pump conditions there are analytical solutions to these equations, which allow one to calculate the parameters of laser radiation in the case of three-level media [14–16]. Real laser systems are calculated by using numerical methods comprised in such commercial software as LasCad [17] and ASLD [18]. However, calculations by these programmes require experimental calibration because of the inaccurate information about the parameters of laser media and various simplifying assumptions. In the literature, the popular laser medium Yb:YAG is most widely investigated [14, 16]. The Yb:KGW medium is not sufficiently studied for predicting the parameters of laser radiation.

We have studied absorption and thermo-optical effects in the laser system shown in Fig. 1. This system with one or two Yb:KGW crystals was used for generating high-power free-running and Q-switched radiation and for regenerative amplification of ultrashort pulses [9, 11–13]. For measuring the pump absorption in passive or lasing regimes one active element was removed from the scheme as shown in Fig. 1 and the power of transmitted pump radiation was measured by a power meter (P).

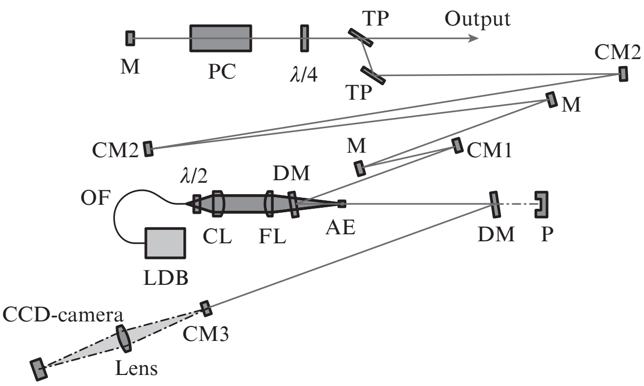

Figure 1. Optical scheme of laser:
(M) plain dielectric mirrors; (PC) Pockels cell; (TP) thin-film dielectric polarisers; (DM) dichroic mirrors; (CM1–CM3) concave mirrors; (AE) Yb:KGW laser crystal; (LDB) laser diode bar; (OF) optical fibre; (CL, FL) collimating and focusing doublets; (P) power meter.

A 3 at.% Yb-doped KGW crystal measuring 1.2×5×5 mm (the thickness is 1.2 mm, length is 5mm, width is 5 mm) with N_g orientation was used as an active element. It was mounted on a copper heat sink through an indium foil and was cooled by a thermo-stabilised water flow. As a pump source we used a fiber coupled laser diode module at 981 nm with an output power up to 70 W. The pump beam from the fibre pigtail of diameter 200 μm with a numerical aperture NA = 0.18 was first collimated by a doublet of lenses with the focal distance f_{CL} = 450 mm and then was focused by one more lens doublet with the focal distance f_{FL} = 750 mm. This focusing scheme provided a constant diameter of the pump beam (of about 330 μm) almost along the entire length of the active medium (with the waist of ~4.8 mm), which was important for efficient pumping. Due to radiation losses on optical elements the maximum pump power on the crystal was ~65 W. Thus, the maximum pump-power density at the crystal entry reached 65 kW cm^{-2} and at the output it was 13 kW cm^{-2} taking into account ~80% absorption, which is substantially greater than the transparency intensity. This condition is also important for providing efficient lasing.

One more important condition for efficient lasing is matching the size of the pump beam with that of the cavity mode in the active element. The mode size for our cavity was calculated by the known method of ABCD-matrices in the geometrical approximation and was matched with the pump beam diameter by longitudinally moving the active element along the cavity axis. The optical scheme of the cavity was chosen to provide its dynamic stability at various levels of the pump power, i.e., a weak dependence of the mode size in the active element on the focal length of the thermo-optical lens induced inside the crystal by absorbed pump radiation. We have studied this problem earlier and results are presented in [11–13].

The spectra of pump radiation and of absorption in the active element (Fig. 2) were accurately matched in order to provide a sufficiently high average absorption efficiency. The temperature shift of the emission spectrum of the laser diode bar with increasing its output power could be partially compensated by changing the diode temperature using a thermoelectric element (Peltier element). The polarisation vector of pump radiation was directed along the N_m axis of the Yb:KGW crystal because this axis is known to have a maximum absorption cross section according to spectroscopic data. Possible depolarisation of pump radiation usually observed in long optical fibres was suppressed, however, not completely, by a relatively short (~30 cm) length of fibre.

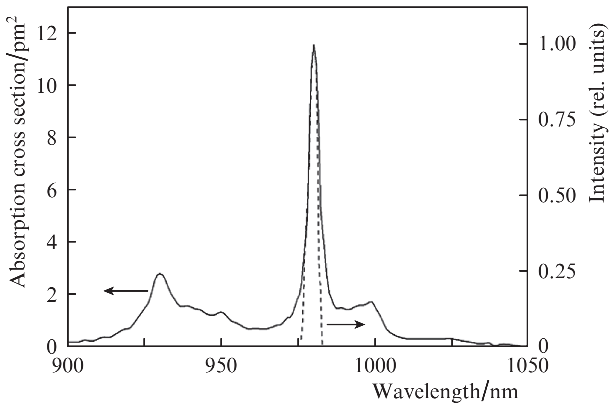

Figure 2. Emission spectra of the laser diode bar (dashed curve) and the transverse absorption cross section of the Yb:KGW crystal (solid curve).

Absorption was measured in two lasing regimes: cw and Q-switched regimes. In the second case, the electro-optical modulation of the Q-factor was performed by the Pockels cell on a double BBO crystal controlled by a high-voltage driver. The pulse repetition rate could be varied from single pulses to 500 kHz.

Measurement results of the pump absorption in the active element are presented in Fig. 3. The temperature of the pump diode bar (T = 37°C) was optimised for obtaining a maximum output laser power at the pump power close to the maximal value (P_{pump} ~ 50 W). In Fig. 3 one can see that the coefficient of pump power absorption in the absence of lasing falls from 0.64 at a low power to 0.45 at a maximal power, which is explained by an increase in the active medium transparency due to saturated absorption. Note that already at the first point of the curve the pump radiation intensity exceeded the transparency value, which reduced the absorption. In addition, at this point there was a substantial (approximately 5 nm) offset of the centre wavelength of diode emission from the maximum of the absorption curve of the Yb:KGW crystal, which also reduces the absorption efficiency. Other reasons for sufficiently low absorption coefficients are a relatively large width of the emission spectrum of the diode bar and approximately 30% depolarisation of pump radiation in fibre. The depolarised radiation cross section for Yb:KGW/Yb:KYW crystals is substantially lower than that of radiation with the polarisation vector directed along the $N_{\rm m}$ axis, which, according to our estimates, leads to approximately 10%–15% losses of the pump power. The employment of laser diodes with a narrower band (2.4 nm) for pumping and suppression of depolarisation makes it possible to increase the absorption efficiency to ~0.8 [19].

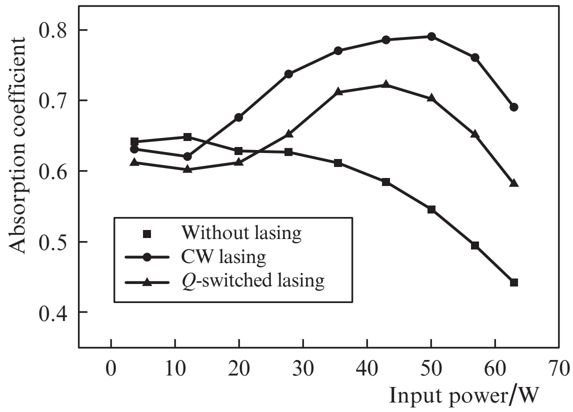

Figure 3. Part of absorbed pump power in the Yb:KGW crystal without lasing and with lasing in the cw and single-pulse regimes at the laser diode bar temperature $T = 37\,^{\circ}$C.

The absorption increases to 0.8 in the cw regime and to 0.72 in the *Q*-switched regime and depends, obviously, on the radiation power density inside the laser crystal, which is lower in the *Q*-switched regime. Part of absorbed power increases due to the rising population of the lower laser level caused by stimulated emission. This behaviour is typical for three-level media. After reaching a maximum absorption efficiency at the level of 0.78, part of absorbed pump power falls to 0.67 and 0.58 for the cw and *Q*-switched regimes, respectively. This fall in the absorption efficiency at a high power may be related to the change in the mode cross section in a crystal due to the action of a thermal lens. Simple calculations using the formalism of ABCD-matrices show that for this cavity configuration the laser mode diameter in the crystal becomes greater than the pump spot [11, 12] and losses grow.

A certain contribution into the change of the pump efficiency is made by reabsorption of laser radiation [14] in 'tails' of the absorption band of the Yb:KGW crystal (Fig. 2). However, such reabsorption does not result in the total losses of laser radiation because it participates in forming the population of the upper lasing level rather than transfers completely to heat.

The influence of the temperature of the copper heat sink of the diode bar on the absorption efficiency is demonstrated in Fig. 4. One can see that the absorption efficiency noticeably falls in a greater part of the range of pump power variation when the temperature differs from the optimal value by more than 2 °C, which determines the required accuracy of temperature maintenance. Therewith, the maximum absorbed pump power (47 W) at the maximum pump power (65 W) is attained at the minimal temperature of the laser diode bar (32 °C) and exceeds the power absorbed at $T = 37\,^{\circ}$C by approximately 8%.

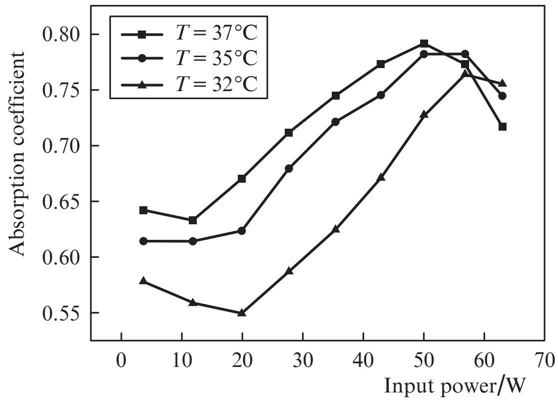

Figure 4. Part of absorbed pump power in the Yb:KGW crystal at various temperatures of the pump diode bar in the cw regime.

All dependences of the absorption efficiency on the pump power are nonlinear. Without lasing, this is related to the dependence of position of the spectral maximum and its shape on the value of the current. A greater current leads to heating of the active zone of the laser diodes and to substantial changes in their emission spectra [20].

Under the conditions of lasing, the nonlinear absorption of radiation is also accompanied by the nonlinear behaviour of inverted population and, hence, of the active medium gain, and by the thermal lens that changes the mode dimension in the active element. All these factors are responsible for sufficiently complicated dynamics of pump absorption.

The absorbed pump power directly affects the lasing power (Fig. 5). The maximum output power of the laser in the cw regime reached 16 W. The absolute optical effi-

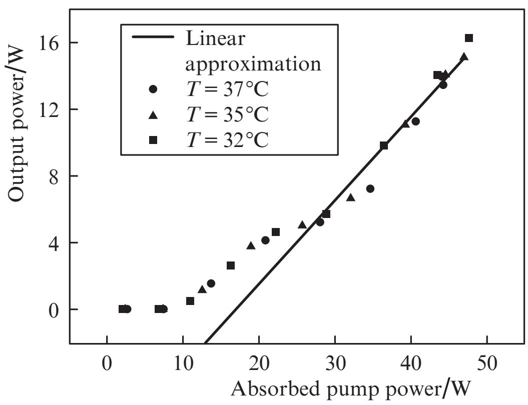

Figure 5. Dependence of the output power of a single-crystal laser on the pump power at various temperatures of the pump diode bar in the cw regime.

ciency of the laser relative to the absorbed pump power increased from 10% near the threshold value to 32% at the maximal pump power. The slope efficiency at high pump powers reached 50%.

3. Thermo-optical effects in a Yb:KGW crystal

The absorbed pump power transferred to heat leads to such thermo-optical effects as the appearance of a thermo-optical lens and radiation depolarisation [1, 2]. Since KGW/KYW crystals are biaxial, they lack depolarisation. However, since thermo-physical constants are not uniform over various axes of these crystals, a strong aberration lens arises, which substantially influences the parameters of both generated and amplified radiation [10–12]. Hence, in optimising the optical scheme of a laser with high average radiation one should know the thermal lens power.

The dioptric power of the thermal lens $D_{\rm th}$ for a Gaussian pump beam profile can be calculated analytically by the formula [21]:

$$D_{\rm th}=\frac{1}{f_{\rm th}}=\frac{\eta_{\rm t}P_{\rm abs}}{2\pi w_{\rm p}^2K}$$

$$\times\left[\left(\frac{\partial n}{\partial T}\right)+(n_0-1)(1+\nu)\alpha_{\rm T}+2n_0^3\alpha_{\rm T}C'_{x,y}\right], \qquad (2)$$

where $f_{\rm th}$ is the focal length of the thermal lens; $P_{\rm abs}$ is the absorbed pump power; $\eta_{\rm t}$ is the efficiency of converting the absorbed power to heat; K is the heat conductivity coefficient; $\partial n/\partial T$ is the derivative of the refractive index with respect to temperature; $w_{\rm p}$ is the radius of the pump beam in the active medium; n is the refractive index; ν is the Poisson coefficient; $\alpha_{\rm T}$ is the thermal-expansion coefficient; and $C_{x,y}$ are the photoelastic constants.

Unfortunately, insufficient accuracy of known thermo-optical and thermo-physical constants included in this equation and deviation of the pump beam from the Gaussian profile related with employment of laser diodes with a fibre pigtail [22] hinder accurate calculations of the focal length of the thermal lens. To this end, we have measured focal lengths for the two most popular configurations of the crystal: $N_{\rm p}$-cut and $N_{\rm g}$-cut (in the first case the laser beam propagates along the $N_{\rm p}$ axis and in the second case – along the $N_{\rm g}$ axis of the KGW crystal). For this purpose, by using a CCD-camera we measured the size of the cavity mode in the lasing regime at the end mirror CM3 as shown in Fig. 1. The focal length of the thermal lens was calculated by comparing the experimentally measured mode size with that calculated by the method of ABCD-matrices. In this case, the thermal lens was presented as two thin cylindrical lenses with mutually perpendicular axes placed in series at the laser crystal centre. In order to carry out sufficiently precise measurements, the cavity should operate in the single-mode regime with a high beam quality, which was controlled by a CCD-camera.

Dependences of the dioptric power of the thermo-optical lens on the pump power for $N_{\rm g}$- and $N_{\rm p}$-cut Yb:KGW crystals are presented in Fig. 6. One can see that the thermal lens for both cuts of the crystal is astigmatic, i.e., the focal distances for two perpendicular cross sections are different. In this case, the lens in the crystal with $N_{\rm p}$ orientation is substantially more astigmatic than in the crystal with $N_{\rm g}$ orientation, which agrees with results of other work [10, 23, 24]. Finally, as one can see from presented images, the beam corresponding to the $N_{\rm g}$ crystal orientation is more symmetric.

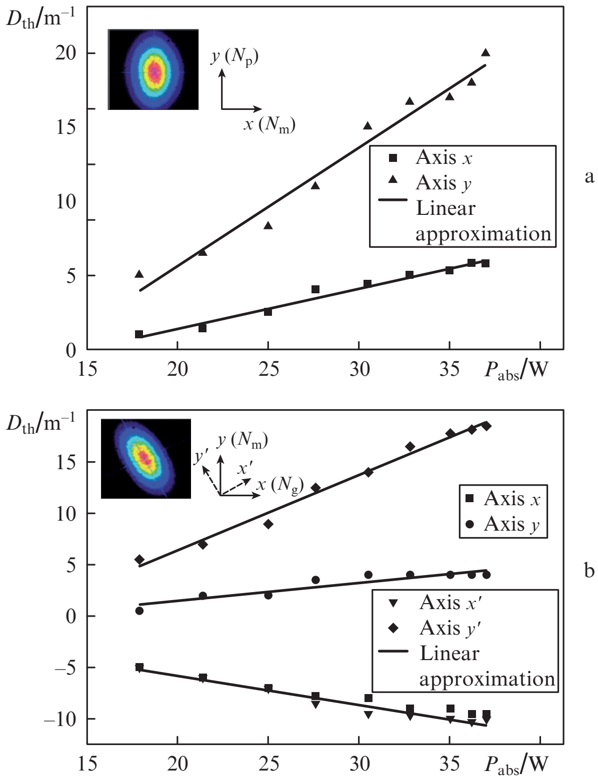

Figure 6. Dioptric power of the thermal lens in the $N_{\rm g}$- (a) and $N_{\rm p}$-cut (b) Yb:KGW crystal vs. absorbed pump power; the polarisation direction is along the $N_{\rm m}$ axis. Insets present typical images of the laser beam on the end mirror CM3.

The dioptric power of the astigmatic thermal lens can be approximated by the empirical linear dependences:

$$D_{\rm th} = kP_{\rm abs}, \qquad (3)$$

where $D_{\rm th}$ is measured in m^{-1}, and $P_{\rm abs}$ – in watts.

For a Yb:KGW crystal with $N_{\rm g}$ orientation the astigmatic axes coincide with the $N_{\rm p}$ and $N_{\rm m}$ axes of the crystal and also with the horizontal and vertical axes x and y. The proportionality coefficients for these axes chosen by the linear approximation method are $k_{\rm m}$ = 0.27 W^{-1} m^{-1} for the cylindrical lens along the $N_{\rm m}$ axis and $k_{\rm p}$ = 0.8 W^{-1} m^{-1} for the lens along the transverse axis $N_{\rm p}$. For the crystal with $N_{\rm p}$ orientation the astigmatic axes x' and y' of the thermal lens (inset in Fig. 6b) are rotated relative to the horizontal and vertical axes by approximately 22°. For the axes x' and y' the proportionality coefficients are $k_{x'}$ = –0.28 W^{-1} m^{-1} and $k_{y'}$ = 0.74 W^{-1} m^{-1}. For the crystal axes $N_{\rm g}$ and $N_{\rm m}$ coinciding with the axes x and y the corresponding coefficients are k_x = -0.23 W^{-1} m^{-1} and k_y = 0.18 W^{-1} m^{-1}.

From the data presented above one can see that for various orientations of the crystal axis as a positive so and a negative thermal lens may arise. The focal length of the lens under the maximum pumping reaches several centimetres, which may strongly affect the laser cavity stability, output power and quality of laser radiation.

4. Conclusions

We have measured the absorption of the InGaAs laser diode bar radiation in Yb:KGW crystals at a high excess of the radiation intensity inside the cavity over the transparency intensity of the active medium. We have shown that without lasing, the absorption efficiency falls from 0.64 to 0.44, which results in the absorbed power saturation. On the contrary, in the lasing regime the absorption efficiency increases with the pump power to 0.78 and then reduces to 0.57–0.67, which leads to less pronounced absorbed power saturation. This behaviour of absorption yields actually a linear dependence of the power of a single-crystal laser on the pump power.

The powers of the thermo-optical lenses induced in laser crystals by the absorbed pump power have been measured. A considerable dependence of the focal power and aberrations of the lenses on the orientation of laser crystals relative to the propagation direction of radiation and to polarisation direction has been observed.

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