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Parameters of the output beam of a longitudinally diode-pumped $YVO_4/Nd:YVO_4$-laser

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Abstract. **The power and spatial characteristics of a longitudinally diode-pumped laser based on a composite $YVO_4/Nd:YVO_4$ crystal are studied. It is shown that the use of a composite crystal allows one to increase the external slope quantum efficiency from 36 % to 41 % and decrease the quality factor M^2 of the output beam from 2 to 1.5 compared to these parameters for a $Nd:YVO_4$ crystal.**

Keywords: *beam quality factor, induced lens, $YVO_4/Nd:YVO_4$ composite crystal, longitudinal diode pumping.*

1. Introduction

Longitudinally diode-pumped high-power solid-state lasers (LDPLs) have a high efficiency and a compact simple design [1, 2]. The problem of improving the output energy characteristics of LDPLs attracts great attention in the literature [3]. However, the spatial properties of laser emission, for example, the quality factor M^2 of the output beam are also important for many applied problems [4]. In the case of high output powers P_{out}, the distribution of the refractive index in an active element (AE) becomes inhomogeneous, the AE ends are deformed and induced birefringence appears [5]. To reduce the effect of these factors on the LDPL characteristics, it was proposed to use composite AEs consisting of the doped and undoped regions [6, 7]. The authors of paper [7] assume that the undoped part of a composite AE can considerably reduce the optical power D of a lens induced in the AE, thereby increasing the output power P_{out} by a factor of 1.5, all other factors being the same.

This paper is devoted to the study of the parameter M^2 of the output beam of a composite $YVO_4/Nd:YVO_4$ LDPL as a function of the pump power and to investigation of the mechanism of influence of the undoped (passive) region of the composite AE on the LDPL characteristics.

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2. Experimental

Figure 1 shows the scheme of a laser longitudinally pumped by a high-power diode laser array. Yttrium orthovanadate crystals doped with Nd^{3+} (Solix LLC) were used as AEs of the laser. Active elements of two types were investigated: with the homogeneous ($Nd:YVO_4$) and inhomogeneous (composite $YVO_4/Nd:YVO_4$ crystal) distribution of activator ions. The atomic concentration of neodymium in $Nd:YVO_4$ was 0.4 %. The active $Nd:YVO_4$ element was a parallelepiped of length 8 mm. The length of the $YVO_4/Nd:YVO_4$ crystal was 10 mm, of which 2 mm are occupied by a passive part (YVO_4) and 8 mm – by the activated $Nd:YVO_4$ crystal with the atomic concentration of neodymium ions of 0.5 %. Both crystals were cut along the *a* axis and had the square cross section with the side 3 – 4 mm. The ends of the crystals were covered with antireflection coatings for the pump (808 nm) and laser (1064 nm) wavelengths.

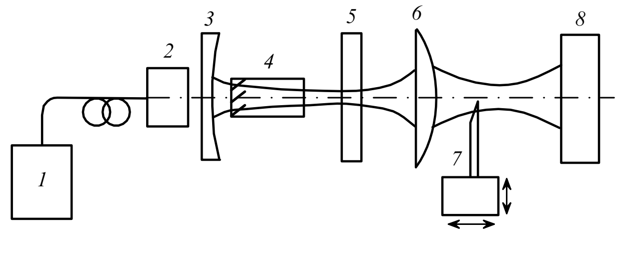

Figure 1. Optical scheme of a longitudinally diode-pumped laser: (*1*) 30-W, 808-nm diode laser array with a fibre pigtail; (*2*) focusing system of the pump unit; (*3*) highly reflecting mirror; (*4*) $Nd:YVO_4$ or $YVO_4/Nd:YVO_4$ active element; (*5*) output mirror; (*6*) lens; (*7*) knife edge; (*8*) power meter.

The $YVO_4/Nd:YVO_4$ crystal was grown as an integral AE. Unlike traditional composite crystals fabricated by the methods of thermal diffusion or gluing, such an AE has no welding boundaries, which introduce additional optical losses into the resonator and produce cracks in the AE at high pump powers. The $YVO_4/Nd:YVO_4$ crystal was oriented in the LDPL resonator by its passive region facing a highly reflecting mirror.

The AE under study was mounted in a water-cooled copper unit. To provide good thermal contact with the cooling unit, the crystal was wrapped with an indium foil. Pumping was performed by a LIMO HLU32F400 diode laser array whose radiation was coupled out through a fibre with a core diameter of 400 μm. The maximum output power of the diode laser array was 30 W. The pump beam was focused in a spot of diameter ~ 500 μm by an optical system with a focal distance of 15 mm mounted at the fibre output.

The laser resonator was formed by a highly reflecting (HR) and an output mirrors. The HR mirror was a spherical mirror with the radius of curvature of 500 mm, a high reflection coefficient at the laser wavelength 1.06 μm, and a high transmission coefficient (~ 99 %) at the pump wavelength 808 nm. The output mirror was a plane mirror with the reflection coefficient 90 % at the laser wavelength. The resonator length was varied from 0.2 to 0.5 m.

The values of M^2 were determined by the method based on the hyperbolic approximation of the dependence of the diameters of the laser beam cross section on the distance along the resonator axis in the vicinity of the beam waist formed by a focusing lens [8]. A lens with a focal distance of 130 mm was placed behind the output mirror of the resonator (Fig. 1). Diameters of the cross sections of the output beam were measured by the method of 'moving knife edge' [9]. The accuracy of the displacement of the knife edge was 1 mm along the laser beam and 10 μm in the perpendicular direction. The radiation intensity propagated through the knife edge was detected with a FieldMaster LM-3 power meter (Coherent).

The optical power D of a lens induced in the AE at a fixed pumped power P_p was determined by the method used in [10]. In this method, the original laser resonator (the HR and output mirrors and the AE with the induced lens) is replaced by an equivalent resonator in which the lens is absent. If the AE is located near the HR mirror and the distance L between both mirrors is much greater than the AE length, the effective radius of curvature R_{eff} of the HR mirror of the equivalent resonator is described by the expression [11]

$$\frac{1}{R_{eff}} = \frac{1}{R} + D(P_p), \quad (1)$$

where R is the radius of curvature of the HR mirror in the original resonator. The fundamental mode of the equivalent resonator is stable if the condition [10]

$$0 < 1 - \frac{L}{R_{eff}} < 1 \quad (2)$$

is fulfilled. It follows from (1) and (2) that for $P_p = \text{const}$ and the critical length of the resonator $L_{cr} = R_{eff}$, the equality

$$D(P_p) = \frac{R - L_{cr}}{RL_{cr}} \quad (3)$$

is fulfilled, the laser resonator becomes unstable, and lasing at the fundamental mode is quenched.

Therefore, by measuring the pump power P_p at which lasing is quenched at a fixed resonator length and varying the value of L, we can determine from (3) the dependence of the optical power D on the pump level of the LDPL.

3. Experimental results and discussion

The output power, the optical power of a lens induced in the AE, and the quality factor of the output beam of the LDPL at different pump levels for Nd : YVO_4 and YVO_4/Nd : YVO_4 AEs are presented in Figs 2 and 3. The measurement accuracy of the output power in the measurements of the dependence of P_{out} on P_p was 1–2 mW. The relative measurement error of the pump power corresponding to laser quenching in the measurements of the optical power of a lends induced in the AE was maximal for the resonator with a base of ~ 0.5 m and was ~ 2 %.

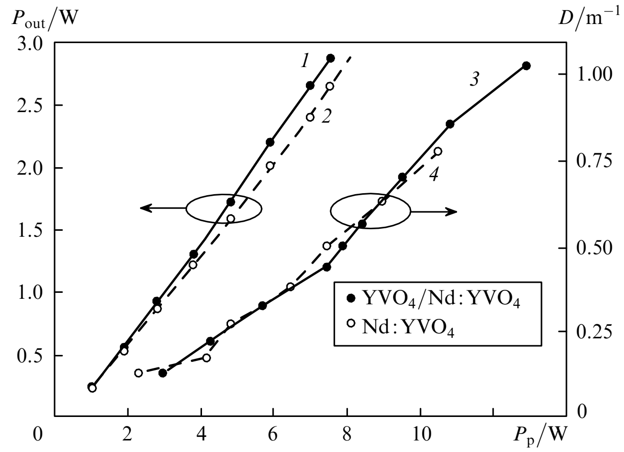

Figure 2. Dependences of the laser output power P_{out} (*1*, *2*) and optical power D (*3*, *4*) of a lens induced in the active element on the pump power for YVO_4/Nd : YVO_4 and Nd : YVO_4 crystals, respectively.

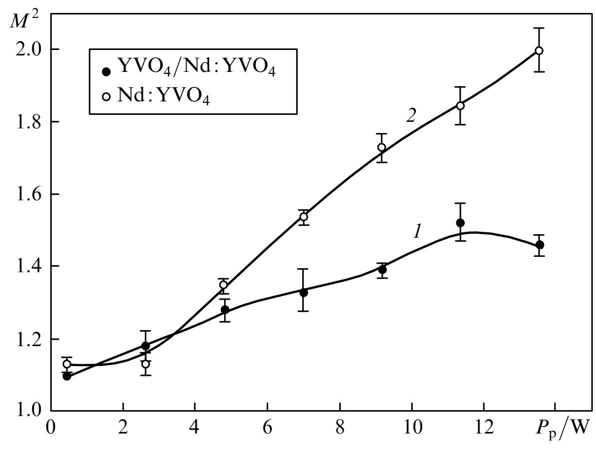

Figure 3. Dependences of the laser-beam quality factor M^2 on the pump power P_p for YVO_4/Nd : YVO_4 (*1*) and Nd : YVO_4 (*2*) active crystals.

A comparison of curves (*1*) and (*2*) in Fig. 2 shows that the composite active YVO_4/Nd : YVO_4 crystal provides the increase in the external slope quantum efficiency from 36 % to 41 % compared to the homogeneously activated AE. However, when the Nd : YVO_4 crystal was replaced by the YVO_4/Nd : YVO_4 crystal, no noticeable decrease in D was observed up to the pump power ~ 14 W [see curves (*3*) and (*4*) in Fig. 2].

At low pump levels of the LDPL P_p ~ 0.5 – 3.5 W, the beam quality factor is approximately the same for both AEs and is 1.1 – 1.2 [Fig. 3, curves (*1*) and (*2*)]. For $P_p > 3.5$ W, the parameter M^2 for the Nd : YVO_4 laser almost linearly increases up to 2 for $P_p = 14$ W, whereas this parameter for the YVO_4/Nd : YVO_4 laser does not exceed 1.5 at the same pump level.

These results show that the use of a composite AE in an LDPL makes it possible to increase the output power of the laser without considerable impairment of its spatial characteristics.

According to curves (*3*) and (*4*) in Fig. 2, the optical powers of lenses induced in Nd : YVO_4 and YVO_4/Nd : YVO_4 crystals are virtually the same. Therefore, the better quality of the output beam of the composite LDPL observed at high pump levels is most likely explained by a decrease in thermoelastic deformations on the AE facet facing the HR mirror. The undoped part of the composite crystal does not absorb pump radiation. Due to the additional scattering of heat in this region, the thermal load on the activated crystal of the composite AE is reduced. The facets of the composite crystal are not distorted noticeably with increasing the output power, which is confirmed in experiments by a weak dependence of the parameter M^2 on P_p.

4. Conclusions

We have shown in this paper that the use of a composite YVO_4/Nd : YVO_4 AE makes it possible to increase the slope lasing efficiency from 36 % to 41 % compared to a Nd : YVO_4 AE, all other factors being the same.

The composite YVO_4/Nd : YVO_4 AE allows one to increase the output power by preserving the relatively high quality of the output beam. Thus, when the Nd : YVO_4 crystal is used, the parameter M^2 rapidly increases up to 2.0 with increasing the pump power up to 14 W, while in the case of the YVO_4/Nd : YVO_4 AE, the rate of increasing $M^2(P_p)$ is reduced more than by a factor of 2.5. For maximum pump levels used in our experiments ($P_p \leqslant 14$ W), the value of M^2 did not exceed 1.5 for a laser with the composite AE.

The optical power of a lens induced in the AE was in fact the same for both active crystals studied in the paper. The improvement of the quality factor of the output laser beam in the composite AE is most likely explained by a weaker deformation of its front facet. However, for better understanding the reasons for improving the parameter M^2 when a composite AE is used, further investigations are required.

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