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Generation in a laser with a tubular active element made of a neodymium-doped potassium – gadolinium tungstate crystal

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***Abstract*. The generation in a laser with an active element made of a neodymium-doped potassium – gadolinium tungstate crystal Nd^{3+}: KGW in the form of a parallelepiped with a coaxial hole for a pump flashlamp is studied. The effect of anisotropy of spectral and laser properties of a Nd^{3+}: KGW laser and of the thermal inhomogeneity of the distribution of laser emission on the output mirror is experimentally demonstrated under conditions when the pump radiation virtually does not return to the medium (the unlimited aperture model).**

Keywords: *solid-state lasers, tubular active element, neodymium-doped potassium–gadolinium tungstate, crystal anisotropy.*

1. Introduction

The optimisation of the design of a reflector and active elements is one of the main methods for increasing the efficiency of flashlamp-pumped solid-state lasers. The basic principles of such optimisation were proposed earlier in Ref. [1]. It was shown that by choosing the reflector geometry that provides an increase in the time of interaction of pump radiation with an active element and by matching the pump radiation with the absorption spectrum of the active element, the absorption of pump radiation by active centres can be substantially increased.

Comparative studies of lasers with reflectors of different designs performed in papers [2 – 5] have demonstrated the validity of such an approach. It was found that the design with a tubular active element, when an active layer surrounds a cylindrical lamp, is one of the most efficient. The theoretical lasing efficiency of such neodymium glass lasers can achieve 25 % relative to the energy deposited into a flashlamp [6]. In practice, the lasing efficiency was 9 % [6], while the efficiency relative to the energy stored in the active element was 8 % [7], which is several times greater than the efficiency typical of a standard pumping system.

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The efficiency of absorption of pump radiation also depends on the concentration of active ions in the active element. One of the promising crystals in this respect is neodymium-doped potassium – gadolinium tungstate Nd^{3+}: $KGd(WO_4)_2$ (Nd^{3+}: KGW). This crystal has a high optimal activator concentration of 3 % ($\sim 2 \times 10^{20}$ cm^{-3}), which is approximately an order of magnitude higher than that in an YAG crystal. Unlike YAG crystals, Nd^{3+} : KGW crystals can be grown in the form of large optically homogeneous samples [8]. However, the use of these crystals in lasers with high average powers is limited by their low thermal conductivity, which is approximately five times lower than that of YAG. The tubular configuration of an active element improves the heat removal upon forced cooling due to an increase in the heat-removal area compared to a conventional configuration.

The Nd^{3+} : KGW crystal belongs to the monoclinic syngony (the space group $C^6_{2h-2/c}$). The axes $\boldsymbol{p}$, $\boldsymbol{m}$, $\boldsymbol{g}$ of the indicatrix of its refractive indices (at $\lambda \approx 1.06$ μm $n_p = 1.937$, $n_m = 1.986$, $n_g = 2.033$) are oriented relative to the crystallographic axes $\boldsymbol{a}$, $\boldsymbol{b}$ and $\boldsymbol{c}$ as $\boldsymbol{p} \| \boldsymbol{b}$, $\angle \boldsymbol{m}, \boldsymbol{a} \simeq 24°$, $\angle \boldsymbol{g}, \boldsymbol{c} \simeq 20°$ [9 – 11]. Active elements are usually cut along the axis of crystal growth coinciding with the $\boldsymbol{b}$ axis. The mutual orientation of the axes in the cross section of such an active element is shown in Fig. 1.

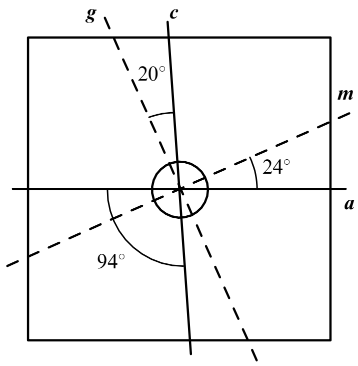

Figure 1. Orientation of axes in the active element.

The polarisation of luminescence is oriented predominantly along the $\boldsymbol{m}$ axis. The effective thermooptic parameter for this polarisation is $\Delta n/\Delta T = 4.3 \times 10^{-6}$ K^{-1} [10]. The absorption spectra of Nd^+ : KGW for different combinations of directions of observation and crystallographic axes are not identical (the absorption coefficients in individual bands differ by a factor of three). The gain also strongly depends on the direction of pump radiation relative to the crystallographic axes [12].

2. Experimental

We studied the effect of anisotropy of the properties of a Nd^{3+} : KGW crystal on the spatial characteristics of output radiation using the model of unlimited aperture of the active element. In this case, the axially symmetric radiation from a pump flashlamp does not return back to the active element by means of some reflector, i.e., it propagates through the active element only once.

In this model, the mixing of pump radiation from different directions is minimised and the anisotropy of absorption in Nd^{3+} : KGW is manifested most distinctly. This model is realised in practice when the pump radiation is strongly absorbed for a single pass in the active element. The thickness of the active element in the radial direction was chosen to provide this condition. According to our data, the averaged absorption coefficient of Nd^{3+} : KGW along the ***c*** axis (Fig. 1) in the wavelength range between 500 and 1000 nm is about 3 cm^{-1}.

For this reason, the pump radiation is attenuated in the active element of thickness 3 mm along the ***c*** axis more than three times. Note that the averaged absorption coefficient along the ***a*** axis is approximately two times lower. Taking this into account, we fabricated the active element in the form of a parallelepiped of size $15 \times 15 \times 30$ mm cut along the ***b*** axis, with operating faces perpendicular to this axis. The pump flashlamp was located in a hole of diameter 4 mm drilled along the axis of the active element.

The combined action of the attenuation of pump radiation and of the absorption anisotropy results in the azimuthal and radial inhomogeneity of the distribution of pump radiation in the active element. This leads to the transverse inhomogeneity of the gain, the gain being maximal near the hole in the regions adjacent to the ***c*** axis.

The active element had a high optical homogeneity and its operating surfaces had no antireflection coatings. As a pump flashlamp, an IFK-20-3 pulsed xenon lamp with the discharge gap of length 30 mm and the nominal electric energy 20 J was used. The lamp was directly connected to a 100-μF capacitor. The pump pulse duration (FWHM) was about 250 μs. The heat in the active element and the pump flashlamp was dissipated by natural cooling. The laser operated in the free-running mode at a pulse repetition period of 1.5 – 3 min, the minimum lasing threshold was approximately 13 J, the excess above the threshold being no more than 1.5.

The resonator of length about 10 cm consisted of flat mirrors of diameter 40 mm with transmission 0.6 % and 3.5 % at the emission wavelength. The resonator was aligned so that the beams perpendicular to its mirrors propagated through the active element parallel to the axis of the pump flashlamp. This position of the mirrors was considered normal, and the output mirror misalignment was counted from it. The kinetics of output radiation was detected over the entire aperture by means of an LFD-2 photodiode (with the time resolution better than 1 μs) and an S1-75 oscilloscope. The near-field radiation distribution (i.e., on the output mirror) integrated over the lasing time was detected with a video camera coupled with a PC.

3. Discussion of results

In the case of small misalignments $\delta\varphi_{|}$ in the vertical plane (Fig. 1), the lasing threshold decreased. The minimum threshold energy was achieved for $|\delta\varphi_{|}^{\rm opt}| \approx 50 \pm 10''$ and it was more than twice lower than the threshold energy in the case of zero misalignment. The decrease in the lasing threshold upon misalignment is obviously caused by the radial thermal inhomogeneity, which can be estimated from the temperature drop over the wall of a tubular active element. This drop amounted to several degrees Celsius at the maximum energy (20 J) deposited to the flashlamp.

Note that such a strong dependence of the lasing threshold on the mirror misalignment has not been observed in conventional resonators. Moreover, this dependence is usually opposite in such resonators, i.e., the lasing threshold increases in the case of the mirror misalignment [13]. This probably can be explained by the specific properties of tubular active elements and by thermal distortions emerging in them.

In a properly aligned laser with a tubular active element, the light beams propagating along the axis of a plane–parallel resonator are deflected by a thermal lens to the active-element axis, i.e., to the inactive region, whereas in conventional resonators these beams enter the region with a higher gain. In this case, the radial dependence of the gain in the tubular active element sharply breaks at the maximum near the edge of the hole, whereas this dependence is continuous in a usual active element. It seems that this discontinuity results in the sharp dependence of the lasing threshold on the mirror misalignment. It is known that a continuous distribution of the pump radiation intensity in a laser rod produces in its central region minimal thermal gradients and a thermal lens, which is close to a spherical lens. In contrast, gradients near the edge of the hole in a laser with the tubular active element are maximal, and the thermal lens is strongly aspherical. For this reason, the beams come out to the inactive region more rapidly, and the dependence of losses on the misalignment increases.

Due to the difference in the integrated absorption along the ***a*** and ***c*** axes, a thermally induced positive lens proves to be axially asymmetric – bifocal (of course, the description of the lens in terms of spherical optics is quite conventional because of its strong asphericity). The minimal focus length, according to the measured value of $\delta\varphi_{|}^{\rm opt}$, is about 15 m. Due to the presence of the bifocal lens, the radiation losses in the regions of the operating aperture to the left and to the right of the hole (Fig. 1) and, hence, horizontal misalignments $\delta\varphi_{-}^{\rm opt}$ corresponding to minimal thresholds will be lower than $\delta\varphi_{|}^{\rm opt}$.

According to geometrical optics, the experimental value $\delta\varphi_{|}^{\rm opt} \sim 1'$ corresponds to the radial variation in the refractive index $\delta n_{|} \sim 10^{-5}$. The same value gives the estimate based on calculation of the heat release in the active element. The corresponding estimate δn_{-} for the horizontal plane yield the value lying within the alignment error ($\sim 10''$). No displacement of the optimal alignment was observed in the experiment upon the output mirror misalignment in the horizontal plane.

The oscillograms demonstrate peaks of the output radiation, which are typical of the free-running mode in solid-state lasers. For the maximum pump energy, two or more regions of transient oscillations were observed, which corresponds to the multithreshold regime (Fig. 2). These properties of the lasing kinetics show that the output beam is divided into several independent channels.

Fig. 3 demonstrates typical transverse distributions of the output radiation as a function of the misalignment angles. The first seven pictures show the radiation distributions for different positive (Figs 3a – d) and negative (Figs 3e – g) resonator misalignments in the vertical plane. According to the unlimited aperture model, the radiation distributions below (Figs 3a – d) and above (Figs e – g) the hole should be similar.

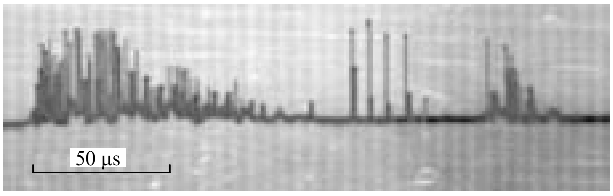

Figure 2. Lasing oscillogram.

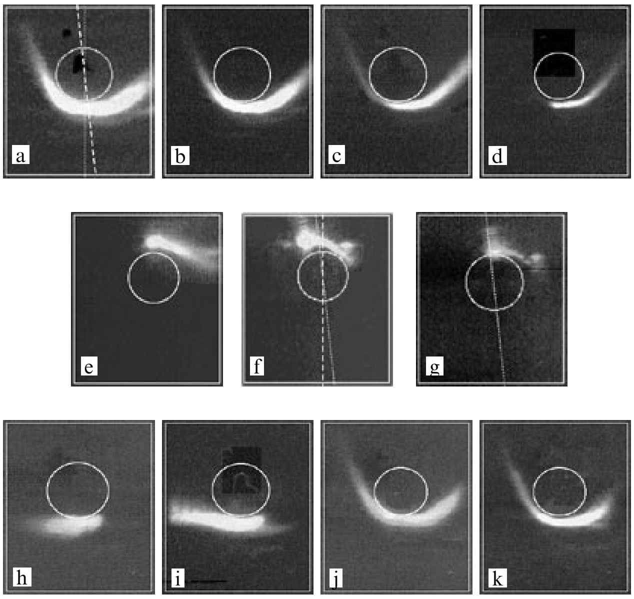

Figure 3. Spatial distribution of the lasing intensity at horizontal and vertical misalignments of the output mirror equal to 0 and 45″ (a), 0 and 1′05″ (b), 0 and 1′15″ (c), 0 and 2′35″ (d), 0 and −1′15″ (e), 0 and −2′05″ (f), 0 and −2′25″ (g), 10 and 15″ (h), 20 and 35″ (i), −10 and 55″ (j), and 4′40″ and −4′15″ (k), respectively.

The difference between these distributions is manifested in a greater extension of the lasing spot in the direction of the upper side of the active element (Figs 3 e – g) and is caused by diffusion reflection from the adhesive layer fixing the active element. Lasing at the left of Figs 3e – g is absent because of the presence of the electric leads from the pump flashlamp. The intensity maxima in the lasing regions above and below the holes are somewhat displaced with respect to the vertical axis. The axis passing through them deviates from the vertical by the angle $4.5 \pm 1.5°$ (see Figs 3a, f, g), i.e., it is parallel to the crystallographic axis ***c*** within the statistical scatter. It is in this direction that the maximum absorption coefficient and the maximum cross section of the laser transition are achieved when the pump flashlamp is parallel to the ***b*** axis. When the misalignment exists simultaneously in both planes (Figs 3h – k), the lasing region as if tends to encompass the hole.

4. Conclusions

We clearly have demonstrated anisotropy of the properties of KGW and the inhomogeneous distribution of the absorbed pump energy in the tubular active element studied upon pumping slightly above the lasing threshold. The laser radiation exhibits the following basic features:

– the azimuthal inhomogeneity of the transverse distribution, which is manifested in the predominant concentration of radiation in the regions of the operating aperture adjacent to the ***c*** axis – hole axis plane in the active element;

– the radial inhomogeneity (radiation is concentrated in the regions adjacent to the hole);

– the increase in the lasing threshold in a properly aligned resonator caused by a thermal lens;

– the division of the lasing region into independent channels.

To manufacture lasers with KGW tubular active elements, it is necessary to provide uniform pumping of the active element, which would minimise thermooptic effects and anisotropy of the spectral properties of the material. This can be achieved by a proper choice of the size and shape of the external surface of the tubular active element (which can differ from a circle) in combination with a diffusion reflector, as well as by using the resonator of a special design compensating for thermooptic distortions in the active element [14]. The latter condition is necessary for efficient tubular lasers, whereas it is not obligatory for conventional lasers.

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