МЕТОДЫ ИЗМЕРЕНИЙ, КОНТРОЛЯ, ДИАГНОСТИКИ

THERMAL LENSING MEASUREMENTS IN THE ANISOTROPIC LASER CRYSTALS UNDER DIODE PUMPING

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An experimental setup was developed for thermal lensing measurements in the anisotropic diode-pumped laser crystals. The studied crystal is placed into the stable two-mirror laser cavity operating at the fundamental transversal mode. The output beam radius is measured with respect to the pump intensity for different meridional planes (all these planes contain the light propagation direction). These dependencies are fitted using the ABCD matrix method in order to obtain the sensitivity factors showing the change of the optical power of thermal lens due to variation of the pump intensity. The difference of the sensitivity factors for two mutually orthogonal principal meridional planes describes the thermal lens astigmatism degree. By means of this approach, thermal lensing was characterized in the diode-pumped monoclinic N_p-cut Nd:KGd(WO₄)₂ laser crystal at the wavelength of 1.067 μm for light polarization $E \parallel N_m$.
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Introduction

As optical pumping of the laser crystal results in the volumetric heat deposition that leads to the complicated refractive index distribution, the active medium can act as a lens (*thermal lens*) [1–4]. It results in dropping of output power, decreasing of output beam quality and poorer laser cavity stability [1, 2]. In general, thermal lensing restricts substantially the laser power scaling capabilities. Optimization of laser cavity in order to eliminate the influence of thermal lensing effects requires information about thermal lens properties. Similarly to a conventional lens, the thermal lens is characterized by the sign (focusing or defocusing action).

However, its optical power is a linear function of pump power (the corresponding slope is usually denoted as the sensitivity factor M) [3]. The M value indicates the change in optical power of thermal lens due to 1W variation of the pump power.

Thermal lensing can be measured by monitoring changes in the laser output [1, 2], or by introduction of an additional probe beam [5, 6]. In both cases, the possibility to determine the beam spatial profile as a function of pump power is available. In addition, during laser operation the influence of thermal lensing on laser mode can be detected from rollover of the output power at high pump powers when the cavity becomes unstable [2, 7].

The second scenario suffers by two reasons: a possibility for multimode operation and influence of mode matching. Indeed, switching to the multimode operation and corresponding output power increase can mask the moment when the laser cavity becomes unstable. Poor overlapping of the pump and laser modes can lead to laser ceasing, even when the laser cavity is still stable.

Measurement of properties of thermal lens with a *probe beam* technique under the diode pumping is complicated by a requirement for pump and probe beams to be overlapped (typically with the precision better than 100 μm). Thus, under diode-pumping conditions the analysis of the output beam spatial profile should be selected as a simple tool for thermal lensing measurements.

Thermal lens in the anisotropic crystals can be substantially *astigmatic* [1] (i.e., its optical power depends on the meridional plane). It leads to elliptic profile of the output beam. The idea of preset paper was to extract the information about astigmatism of the thermal lens from measurements of divergence of the output beam performed for different meridional planes. In addition, these measurements were performed with respect to the pump intensity $I_{in} = 2P_{in}/\pi\omega_p^2$ (P_{in} is the pump power, ω_p is the pump mode radius) resulting in the novel definition of the sensitivity factor. Using this approach, thermal lensing was characterized for monoclinic $Nd:KGd(WO_4)_2$ laser crystal under diode pumping at the wavelength of 1.07 μm for light polarization $E \parallel N_m$.

Measurement technique

The schematic of the thermal lensing measurements by monitoring the changes in the laser output is the following:

1) the orientations of the principal meridional planes A and B that correspond to the major and minor semiaxes of the output beam elliptic profile are determined;

2) the output beam radii ω_A and ω_B are measured with respect to the pump intensity at some fixed distance from the output coupler;

3) these dependencies are fitted using the ABCD matrix method in order to obtain the sensitivity factors showing the change of the optical power D of the thermal lens due to variation of the pump intensity $M = dD/dI_{in}$;

4) the difference of the sensitivity factors for principal meridional planes $S = |M_B - M_A|$ (thermal lens astigmatism degree) is determined.

The key point is the correct ABCD-modeling of the laser cavity, which suffers from the uncertainty in the distances between all optic elements that form the laser cavity [2]. Indeed, for the real laser scheme these distances can be measured with some precision (typically not better than 0.5 mm). The increase of the element number results in the increase of the overall error. Thus, the laser cavity should be rather simple (formed by *two mirrors* with laser crystal positioned between them).

Secondly, the chosen laser cavity should be rather sensitive to influence of thermal lensing effect and to remain stable within the whole possible region of pump intensities. Here the important issue is the model applied for the description of thermal lens. Typically the feature of the diode-pumping is the small crystal thicknesses accompanied by a short absorption length. When the pump radiation is absorbed within the short region near the input crystal face, the heat deposition (and refractive index variation) is highly localized. Thus, the thin lens model could be applied, this lens in positioned near the input crystal face.

When the laser operates in the multimode regime (the M^2 parameter is higher than 1), ABCD modeling of the cavity could still be performed. However, it introduces significant error due to uncertainty in the beam radius measurements. Thus, in order to achieve high accuracy, the laser should operate in fundamental transversal mode.

Figure 1 represents the schematic of the two-mirror laser cavity. Here d_1, d_2 are the distances from the mirrors to the laser crystal, d (n) is the crystal thickness (refractive index), R_1 and R_2 are the mirror radii, L is the distance form the output coupler to the measurement plane, D is the optical power of thermal lens.
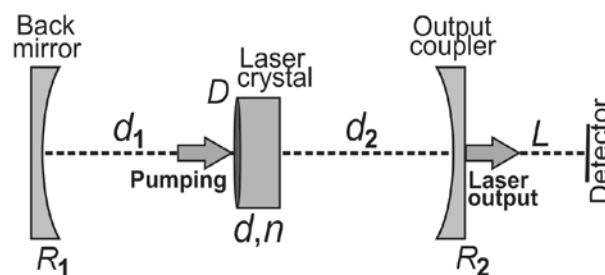

Figure 1 – Schematic of the two-mirror cavity

For a resonator with concave back mirror (R_1 = 50 mm), flat output coupler and symmetric position of the laser crystal ($d_1 = d_2$, d = 1 mm, n = 2), thermal lens results in sufficient distortion of the output mode profile – (figure 2). Positive lens

results in he beam expansion, while negative one – in the beam compression. Thus, the lens sign can be determined unambiguously.
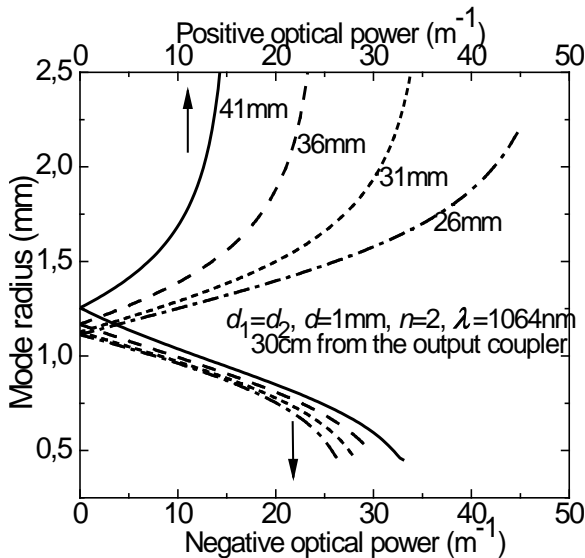

Figure 2 – Calculated dependence of the output mode radius on optical power of thermal lens for *symmetric* laser cavity formed by concave back mirror and flat output coupler (for different cavity lengths)
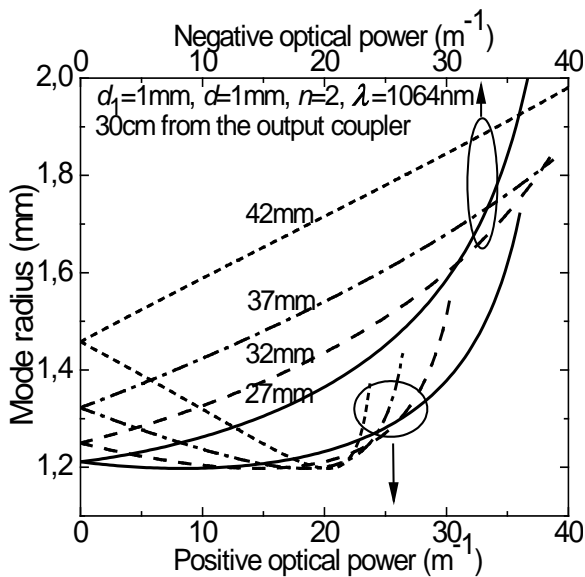

Figure 3 – Calculated dependencies of the output mode radius on the optical power of thermal lens for *asymmetric* laser cavity formed by a flat back mirror and a concave output coupler (for different cavity lengths)

For both signs of the lens the laser cavity becomes unstable at some critical value of optical power of thermal lens $|D_c|$. Shortening of the cavity

results in increase of $|D_c|$ for positive lens and in slight decrease of $|D_c|$ for negative lens. Thus, there is some optimal cavity length (~ 26 mm) which provides laser operation up to high pump powers for both lens signs.

When the laser element is positioned near the flat back mirror (laser cavity is asymmetric, $d_1 = 1$ mm $<< d_2$, $d = 1$ mm, $n = 2$), and the cavity is terminated by a concave output coupler ($R_1 = 50$ mm), the influence of thermal lens on the output beam is qualitatively different (figure 3). In this case, negative lens leads to beam expansion. For small optical powers, positive lens leads to beam compression. Thus, the sign of thermal lens can also be determined unambiguously. However, higher optical power of positive lens leads to beam expansion (this effect is more pronounced for short laser cavities); therefore it is more difficult to determine the lens sign.

Providing the inner and outer surfaces of the output coupler are of the same radii of curvature, it does not affect the divergence of the laser beam. On the contrary, when the inner surface of the output coupler is concave and the outer one is flat (as it is drawn in figure 1), it acts as a lens with focal length $f = -R_2/(n_2 - 1)$ (where $n_2 \sim 1.5$ is the refractive index of the glass) [2]. Thus, such a mirror affects significantly the beam divergence. Another factor that should affect the beam diameters is the M^2 parameter of the beam. For real laser systems, it is close to 1 (typically within the range of 1,1–1,2). This factor is especially pronounced for laser cavities approaching the unstable operation mode. The above mention effects are presented in figure 4.

Optical power of thermal lens for diode-pumped laser crystals is linearly proportional to the pump intensity. If the measured dependence of the output mode radius on the pump intensity $\omega(I_{in})$ is fitted by the calculated dependence of the output mode radius on the optical power of thermal lens $\omega(D)$, the thermal lens sensitivity factor M can be extracted from this fitting. In this case, M is a *scaling factor* that should be introduced in order to superpose both dependencies. The definition of M as the dD/dI_{in} derivative is more suitable for real laser systems than the definition as the dD/dP_{in} derivative. Indeed, in different experiments different pumping conditions can be utilized. Thus, the pump intensity will be different, although the pump power is the same.

As a final remark, for the laser cavities described in figure 2, the major semiaxis of the elliptic laser beam profile (*A*) will correspond to the

meridional plane with maximum optical power of thermal lens. The minor semiaxis (B) will then correspond to the minimum optical power of thermal lens. Thus, thermal lens astigmatism degree S equals $S = M_A - M_B$. On the contrary, for the laser cavities described in figure 3, the directions of $A(B)$ axes will correspond to minimum (maximum) optical power of thermal lens, correspondingly. Thus, thermal lens astigmatism degree equals $S = M_B - M_A$.
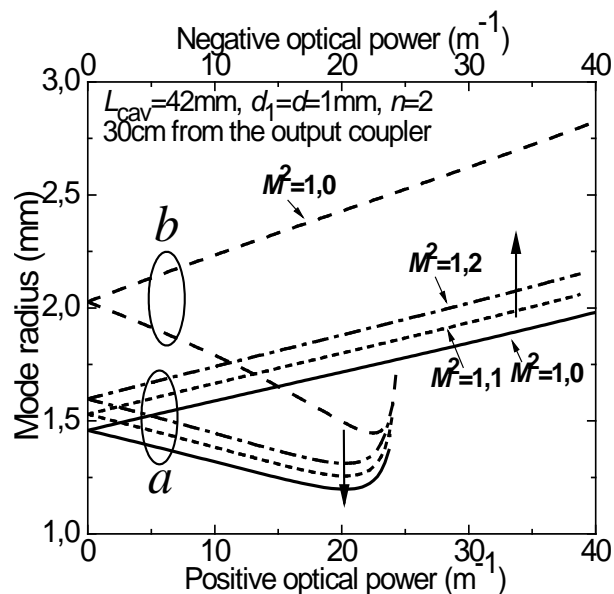

Figure 4 – Influence of the output coupler shape and the M^2 factor on the divergence of the output radiation for *asymmetric* laser cavity: a – inner and outer surfaces of the output coupler have the same radius of curvature, b – the inner surface of the output coupler is concave and the outer one is flat

The special case is the laser materials with extremely strong thermal lensing effects (which can be caused by low thermal conductivity, high quantum defect, intense pumping or poor cooling). Under these conditions, effects of thermal lensing cause significant change of the laser cavity stability conditions. The dependence of the stability parameter g on the cavity length for various focal lengths of thermal lens $f = 1/D$ is presented in figure 5 for asymmetric laser cavity ($d_1 = 1$ mm $<< d_2$, $d = 1$ mm, $n = 2$) with flat back mirror and concave output coupler ($R_1 = 50$ mm). Here the stability parameter equals $g = 1 - [trM_{cav}]^2/4$, where trM_{cav} is the trace of the ABCD-matrix of the cavity (cavity is stable for $0 < g < 1$). Stability regions are marked by hatching.
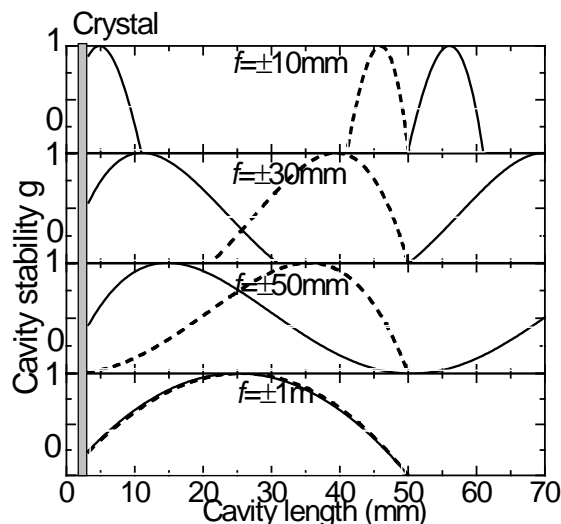

Figure 5 – Calculated dependence of the cavity stability parameter on the cavity length for *asymmetric* laser cavity formed by a flat back mirror and a concave output coupler: *solid* (*dashed*) curves correspond to positive (negative) thermal lens, stability regions are marked by hatching

When the thermal lens is weak and positive ($f = 1$ m), the cavity is stable as soon as the cavity length is shorter than 50 mm (shorter than R_2). When optical power of thermal lens $D = 1/f$ increases, the second stability region for cavities longer than 50 mm arises. If the focal length is further shortened down to 10 mm, both these regions are narrowed. On the contrary, laser cavity with negative lens demonstrates one stability region (for cavity lengths shorter than 50 mm). Some laser crystals are characterized by thermal lens with different signs for different meridional planes. The intersection of the stability regions for different-signed lenses continuously decreases with the optical power increase. When the thermal lens focal length equals 10 mm, the laser with such a cavity could not operate.

Experimental

By means of the described approach, thermal lensing was characterized in the diode-pumped monoclinic Nd(3at.%)-doped potassium gadolinium tungstate laser crystal (Nd:KGd(WO$_4$)$_2$, or Nd:KGdW). The crystal was cut for light propagation along the N_p optical indicatrix axis (that coincides with crystallographic axis b) [6]. The laser cavity was formed by a concave back mirror ($R_1 = 50$ mm, HT@810 nm, HR@1067 nm) and a flat output coupler (HR@1067 nm), the cavity dimen-

sions was $d_1 = 13$ mm, $d = 1$ mm and $d_2 = 13$ mm. The crystal was pumped at 810 nm by the fiber-coupled AlGaAs laser diode, the pump spot radius in the crystal was 180 μm. The measurement plane was positioned at 110 mm from the output coupler. The laser crystal has the thickness of 1 mm and face dimensions of 3×2 mm, both faces were anti-reflection-coated for light wavelengths of 810 nm and 1067 nm. It was maintained at the temperature of 17 °C by means of a brass plate. The output radiation was linearly polarized in the direction of N_m optical indicatrix axis ($E \parallel N_m$), the laser wavelength was 1067 nm. The laser beam profiles were captured by means of a CCD-camera. Thermal lens was considered as a thin one, as the absorption length in the Nd:KGdW at 810 nm for light polarization is shorter than 300 μm [8].

Results

At low pumping levels the Nd:KGdW laser is characterized by circular output mode profile. However, when the pump power is increased, the output mode profile becomes elliptic (figure 6). The major semiaxis of this profile (A) can be found by ~30° clockwise rotation form the direction of output beam polarization ($E \parallel N_m$), when the light propagation direction is pointing away from the observer.
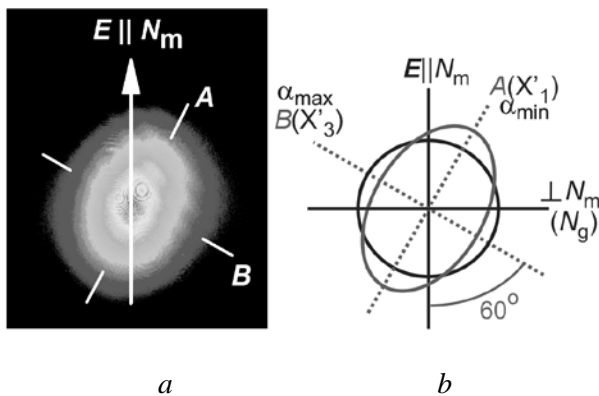

Figure 6 – Output beam profile captured at high pump levels (*a*), schematic of the output beam distortion (*b*) for diode-pumped Nd:KGdW laser

Figure 6 also represents the schematic of the output beam distortion under influence of thermal lensing. The beam expands in the direction of A axis and compresses in the direction of B axis. It should be noted that the orientation of these axes (principal meridional planes) corresponds to principal frame of thermal expansion tensor for KGdW crystal [9]. Indeed, A axis coincides with the X'_1

axis and the B one – with the X'_3 axis. In the measurement plane (N_m-N_g plane), the X'_1 corresponds to the minimum thermal expansion coefficient, while X'_3 axis – to the maximum thermal expansion coefficient.

For the utilized laser cavity configuration, the dependence of the output mode radius on the optical power of thermal lens is similar to one represented in figure 2. Thus, the optical power of thermal lens is positive along the $A(X'_1)$ direction and negative along the $B(X'_3)$ one. Therefore, thermal lens has different signs for rays lying in different meridional planes.

Measured dependencies of the output beam radius on the pump intensity in the principal meridional planes for diode-pumped Nd:KGdW laser are presented in figure 7. In addition, this figure represents calculated dependencies of the output beam radius on the optical power of thermal lens; the appropriate scaling factors were introduced in order to superpose both theoretical and experimental dependencies. These scaling factors are thermal lens sensitivity factors: $M_A = +0.26$, $M_B = -0.47$ [10^{-3} m^{-1}/(W/cm^2)]. Thus, the thermal lens astigmatism degree equals $S = M_A - M_B = 0{,}73 \cdot 10^{-3}$ m^{-1}/(W/cm^2).
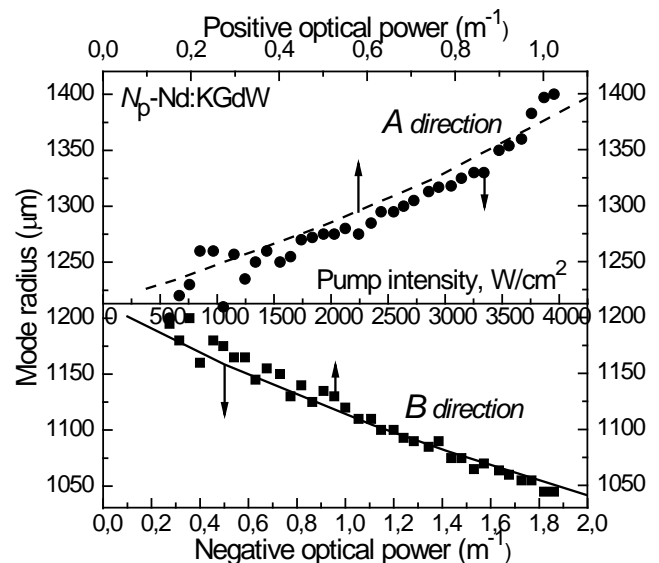

Figure 7 – Measured dependencies of the output beam radius on the pump intensity in the principal meridional planes (*points*), calculated dependencies of the output beam radius on the thermal lens optical power (*curves*) for diode-pumped Nd:KGdW laser

Thermal lens parameters determined in present paper agree well with previous results obtained for flashlamp-pumped N_p-cut Nd:KGdW at the wavelengths of 633 and 1064 nm [5]: thermal

lens was found to have different signs along principal meridional planes that corresponds to the X'_1 and X'_3 axes. In [7, 10], thermal lens in the N_p-cut diode-pumped Nd:KGdW was found to have different signs at the light wavelengths of 1067 and 1351 nm, but the principal meridional planes were not determined. In [6, 11], thermal lens in the flashlamp-pumped N_p-Nd:KGdW was found to be negative (the study with respect to meridional planes was not performed).

Conclusions

An experimental setup was developed for measurements of thermal lensing in the anisotropic diode-pumped laser crystals. The studied crystal is placed into the stable two-mirror laser cavity operating at the fundamental transversal mode. The output beam radius is measured with respect to the pump intensity for different meridional planes. The obtained dependencies are fitted using the calculat-ed dependencies of the beam radius on the optical power of thermal lens in order to obtain thermal lens sensitivity factors M. The M parameters show the change of the optical power of thermal lens due to variation of the pump intensity. The difference of the sensitivity factors for principal meridional planes describes the thermal lens astigmatism degree S. By means of this approach, thermal lensing was characterized in the diode-pumped N_p-cut Nd:KGd(WO$_4$)$_2$ laser crystal at the wavelength of 1.067 μm for light polarization $\boldsymbol{E} \parallel N_m$.

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Определение параметров термической линзы в анизотропных лазерных кристаллах в условиях диодной накачки

Создана экспериментальная установка для определения параметров термической линзы в анизотропных лазерных кристаллах в условиях диодной накачки. Активный элемент на основе исследуемого кристалла помещается в устойчивый двухзеркальный резонатор с TEM_{00} модой выходного излучения. Для различных меридиональных плоскостей экспериментально определяются зависимости радиуса моды выходного излучения от плотности мощности накачки. Моделирование этих зависимостей при помощи методов матричной оптики позволяет определить коэффициенты чувствительности и степень астигматизма термической линзы. При помощи данной методики экспериментально определены параметры термической линзы в моноклинном кристалле $\text{Nd:KGd(WO}_4)_2$ в условиях диодной накачки на длине волны 1067 нм для поляризации света $\boldsymbol{E} \parallel N_{\text{m}}$. (E-mail: kyumashev@bntu.by)

Ключевые слова: лазерный кристалл, диодная накачка, термическая линза, анизотропия.