Thermal lens study in diode pumped N_g- and N_p-cut Nd:KGd(WO$_4$)$_2$ laser crystals

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Abstract. A comparative study of thermal lensing effect in diode laser pumped N_g- and N_p-cut Nd:KGd(WO$_4$)$_2$ (KGW) laser crystals was performed for laser emission polarized along the principle refractive axis, N_m. The thermal lens in the N_g-cut Nd: KGW was found to be weakly astigmatic with a positive refractive power for both the N_m- and N_p-directions. For N_p-cut Nd:KGW, strong astigmatism was observed and the refractive powers in the N_g- and N_m-directions had opposing signs. The degree of astigmatism was found to be considerably weaker for the N_g-cut Nd:KGW in comparison with the N_p-cut one: 0.35 dptr/(W/cm^2) and 2.85 dptr/(W/cm^2), respectively. The ratio of the thermal lens refractive powers in the planes parallel and perpendicular to the laser emission polarisation were measured as + 1.4 and −0.425 for N_g- and N_p-cut Nd:KGW respectively.

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1. Introduction

Neodymium-doped KGd(WO$_4$)$_2$ (KGW) is a well known laser material with extensively investigated spectroscopic properties (see [1–5] and references therein). Nd:KGW has good prospects for self-Raman conversion to 1.54 μm [7,8] due to the relatively high emission cross-section at ~1.35 μm (7.6 × 10^{-20} cm^2 [6]) also in combination with a high Raman gain coefficient (up to 4.4 cm/GW [1]). This is of specific relevance when the laser is operated in the picosecond time domain [9]. This so-called 'eye-safe' spectral range is attractive for realization of high frequency range finders at 1.54 μm, and atmospheric CO$_2$ monitoring [10] at 1.57-1.6 μm (via Raman conversion in Ba(NO$_3$)$_2$). Power scaling in tungstates is, however, limited compared to Nd:YAG lasers, as the thermal conductivity coefficients are approximately 3 times lower [5]. Commercially available N_p-cut Nd:KGW possess strong cylindrical thermal lensing [11], which is difficult to compensate by cavity design alone or by means of adaptive optics [12]. The output power obtainable from tungstate lasers under high power pumping is therefore substantially reduced. Moreover, the poor thermo-optical characteristics typical of tungstates limit its application as effective Raman crystal specifically for high-energy nanosecond pulse operation.

However, there exists a distinctive feature of the KGW crystal which may significantly improve this performance, namely, the negative coefficients of the temperature dependence of the refractive index, *dn/dT,* for some light polarizations and propagation directions (e.g. −0.8 × 10^{-6} K^{-1} for k//N_p, E//N_m) [13–15]. In fact, exploitation of this feature has led to higher output powers being obtained at ~1 μm compared with similar Nd:YAG lasers under high power flash-lamp pumping - average output powers of 40 W at 1.4 kW of pumping was obtained from an N_g-cut Nd:KGW crystal laser which compares favourably with 15 W of output from a similarly configured Nd:YAG laser [16]. In the same configuration, the more conventional N_p-cut Nd:KGW crystal laser ceased operating at only 0.5 kW of average pump power. In another demonstration, an end-pumped N_g –cut Yb:KGW crystal produced ~5 W of laser output power with a near-diffraction limited beam quality [17] under 18 W pumping. The key point of these examples was the exploitation of the special, often called *athermal,*

direction of propagation within the KGW crystal, where the temperature- and stress-dependent refractive indices compensate each other, resulting in significantly lower thermal lensing [13–15]. The direction along the principle refractive axis N_g has been identified as being one of these *athermal* directions, although other orientations are also possible [13,15]. Such 'smart-cut' tungstate crystals therefore show great promise for flexible thermal management, giving access to a wider range of applications including self-Raman conversion.

In this paper, we will compare the thermal lensing effect in two diode laser pumped Nd:KGW lasers having the light propagation direction along the principle refractive axes N_g and N_p (hereafter denoted as N_g-cut and N_p-cut Nd:KGW crystals, respectively). As a result the thermal lensing sensitivity factors, M, for these crystals can then be determined and the degree of thermal lens' astigmatism for both crystals can be calculated and compared. This factor M - the rate at which the thermal lens refractive power varies with pump power intensity - then provides a convenient measure to compare the induced thermal lensing in different laser crystals and orientations [18]. The degree of astigmatism here is the difference between the values of thermal lens refractive power per pump intensity (i.e. between the values of the factor M) in the plane of polarization (N_m) and in the perpendicular plane - a typical measure of astigmatism in, for example, ophthalmology [19].

2 Experimental

The Nd:KGW crystal was grown from the flux by using $K_2W_2O_7$ as a solvent. The modified Czochralski technique was used under conditions of low thermal gradient [20]. The N_p-cut Nd:KGW laser gain medium was grown along the crystallographic axis b which is parallel to the principle refractive axis N_p, whereas, the N_g-cut Nd:KGW material was grown along the crystallographic axis c (the angle between the c- and N_g-axis is 21.5° [21]). Other properties of the N_p- and N_g-cut Nd:KGW crystals were identical.

In all the experiments described here, the N_g-cut and N_p-cut Nd:KGW crystals had a doping level of 7 at. % neodymium and a length of $l = 1.9$ mm. One polished end-face served as a flat laser cavity mirror - a multi-layer dielectric coating was applied to this face to provide both a high-reflectivity at the laser wavelength of 1.35 µm and antireflection at 808 nm (i.e the pump wavelength). The coating also provided minimal reflectivity at 1.067 µm to prevent any parasitic laser oscillation at this wavelength. The other crystal end-face was antireflection-coated for both 1.35 and 1.06 µm. The laser crystal was mounted on a thermo-electric cooled brass plate and the temperature was controlled to 15 °C. Finally, the linear laser cavity was terminated by a concave output coupler having a radius of curvature of $R = 50$ mm and a reflectivity of 99% at 1.35 µm.

The experiments reported here were intentionally performed at a laser oscillation wavelength of 1.35 µm due to the thermal effects in the Nd:KGW laser crystal being higher at this wavelength in comparison to oscillation at 1.067 µm. The diode lasers emitting at a wavelength of 808 nm were used as the end-pumping sources for the laser set-up. The N_p-cut Nd:KGW crystal was quasi-continuously pumped with the emission being linearly polarized along the N_m optical indicatrix axis. Pump radiation was focused into the crystal to a spot with the diameter of 75 µm. The N_g-cut Nd:KGW crystal was continuously pumped by the fiber-coupled laser diode with unpolarized emission. The pump spot into the N_g-cut Nd:KGW crystal was symmetric with the diameter of 150 µm.

Length of the crystals (1.9 mm) and doping concentration (7 at. %) provided 98.8% absorption of unpolarised pump emission at 808 nm and ~99.2% absorption of the polarized pump emission at the same wavelength. We believe the difference in absorption coefficients for polarizations along different crystal axes makes negligible impact on the measurements. The emission of the N_g- and N_p-cut Nd:KGW lasers is polarised along the N_m-axis, and the lasers were configured to emit a fundamental TEM$_{00}$ spatial mode.

Resonator lengths of 26 mm for the N_g-cut Nd:KGW and of 49 mm for the N_p-cut Nd:KGW crystals were chosen to provide the highest output power. The reason for different values of the resonator length will be given below.

Different techniques can be applied to determine thermal lens in laser crystals: measurements of the changes of the output beam characteristics for stable resonator operating at TEM_{00} mode [11,17] and for the resonator close to instability region [16,22]; measurements of the changes in the spatial profile of the probe beam which is passed through a gain medium [22,23]; interferometric measurements [13,24].

Two methods were employed in the present paper to determine the sensitivity factor M. In the first method, the output beam characteristics are measured with respect to the distance from the output coupler at different pump intensities, $P_p/\pi w_p^2$, where P_p and w_p are the pump power and the $(1/e^2)$ Gaussian radius of the pump beam, respectively. The measurements are performed by the knife edge method [22] in two directions: parallel to the N_m-and N_g-axes for the N_p-cut Nd:KGW laser crystal, and parallel to the N_m- and N_p-axes for the N_g-cut Nd:KGW system. Measured output beam size dependencies on the distance from the output coupler are then simulated using the ABCD matrix method [18]. In these calculations, thermo-optical distortions within the gain medium are described by an astigmatic thermal lens of refractive power, D, which is dependent on the pump intensity. The sensitivity factor M is then obtained from the slope of the dependence of thermal lens refractive power versus the pump intensity.

The second method is based on the observation of substantial changes in the spatial and power characteristics of the laser output indicative of the laser resonator becoming unstable due to an action of thermal lensing [22]. Here, the output power of the laser is monitored as a function of the pump intensity at a given cavity length. The pump intensity, $(P_p/\pi w_p^2)_c$, at which the output power begins to reduce is assumed to induce in the gain medium a thermal lens with a critical refractive power, D_c, corresponding to the edge of the cavity stability on the g_1^*-g_2^* diagram [18,22]. The sensitivity factor M is then calculated as the ratio of this critical refractive power D_c to the value of $(P_p/\pi w_p^2)_c$. It should be noted that, in the case of an astigmatic thermal lens, this method provides information on the sensitivity factor in one propagation plane only – i.e. the plane that approaches the stability edge at the least pump power.

3 Results and discussion

The typical measured dependence of the output beam mode diameter with distance from the output coupler for both the N_g- and N_p-cut Nd:KGW lasers are shown in Fig. 1. From these data, it is clear that for the N_g-cut Nd:KGW laser, the output beam suffered compression in both N_m-and N_p-directions with increasing pump intensity (Fig. 1(a, b)). The compression along the N_m-direction was notably greater than that observed along the N_p-axis. However, in the case of the N_p-cut Nd:KGW laser (Fig. 1(c, d)) as the pump intensity increases, the size of the output beam decreases along the N_m direction but increases along N_p. It follows from a calculation of the laser mode behaviour outside the laser cavity that a decrease in the mode size corresponds to an inducted positive thermal lens within the gain crystal, whereas a defocusing lens induces an increase in the mode size. From this ABCD matrix analysis the data of Fig. 1 can be fitted to values of the induced refractive power of the gain crystal, and these are shown as solid, dashed and dotted lines in the figure. Therefore, it is clear that the thermal lenses induced in the N_g- and N_p-cut Nd:KGW active elements are both astigmatic. For the N_g-cut Nd:KGW, the refractive powers of the thermal lens are distinguished in magnitude in the N_m- and N_p-directions, however, they both have the same sign (i.e. positive). This is in contrast to the N_p-cut Nd:KGW case where the refractive powers have opposite signs in the N_m- and N_g-directions (positive and negative respectively).
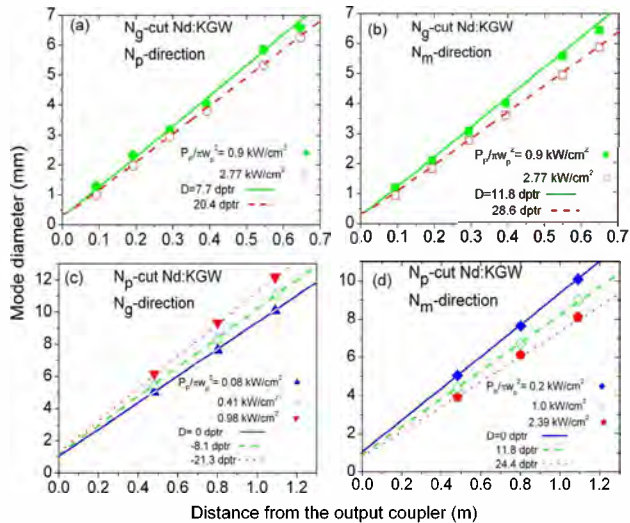
Fig. 1. Dependence of the output beam mode diameter as a function of the distance from the output coupler at different pump intensities $(P_p/\pi w_p^2)$ for the N_g- and N_p-cut Nd:KGW lasers (cavity length is 26 mm for the N_g-cut Nd:KGW laser and 49 mm for the N_p-cut Nd:KGW one). Symbols – experimental data. Lines – results of calculations according to the ABCD-method.

The dependences of the thermal lensing as a function of pump intensity for the N_g-and N_p-cut Nd:KGW crystals were measured and are shown in Fig. 2. As expected from theory [22], these dependences are linear with pump intensity, and from the respective gradients of the data the thermal lensing sensitivity factors M can be calculated - these were found to be, in units of dioptric power per (W/cm^2):

$(M_{Ng-cut})_{Nm} = 1.2 \times 10^{-2}$ (N_g-cut Nd:KGW, N_m-direction),

$(M_{Ng-cut})_{Np} = 0.85 \times 10^{-2}$ (N_g-cut Nd:KGW, N_p-direction),

$(M_{Np-cut})_{Nm} = 0.85 \times 10^{-2}$ (N_p-cut Nd:KGW, N_m-direction), and

$(M_{Np-cut})_{Ng} = -2.0 \times 10^{-2})$ (N_p-cut Nd:KGW, N_g-direction).

The degree of astigmatism [19] for the N_p and N_g-cut Nd:KGW crystals can now be calculated as a difference in corresponding M factors in the plane of polarization (N_m) and in the perpendicular plane:

N_g-cut Nd:KGW: 0.35 dptr/(W/cm^2);
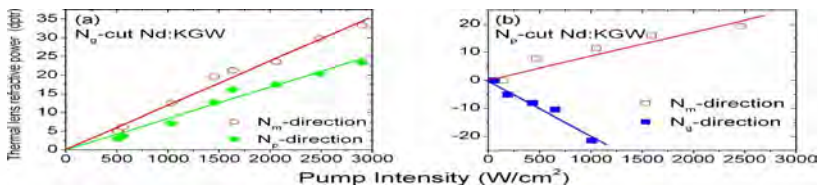
N_p-cut Nd:KGW: 2.85 dptr/(W/cm^2).

Fig. 2. The dependence of thermal lensing on pump intensity $(P_p/\pi w_p^2)$ in diode laser pumped (a) N_g-cut -and (b) N_p-cut Nd:KGW lasers. Symbols – experimental data on thermal lens refractive power. Solid lines –linear fit to the data.

Resonator with the length of 49 mm for the N_p-cut Nd:KGW provided the widest stability region against the negative thermal lensing (which was found to be stronger in this crystal than the positive one), while the N_g-cut Nd:KGW laser with the cavity length of 26 mm was

about two times more stable against positive thermal lensing in comparison with the cavity length of 49 mm (see the calculated critical values of the thermal lens refractive power below). The difference in the resonator length for two Nd:KGW crystals does not influence the measurements of the thermal lens, as the calculations of the beam profile outside the cavity are performed separately for the given cavity length.

The measured output power dependence on pump intensity $(P_p/\pi w_p^2)$ for the N_p-cut and N_g-cut Nd:KGW lasers is presented in Fig. 3(a).
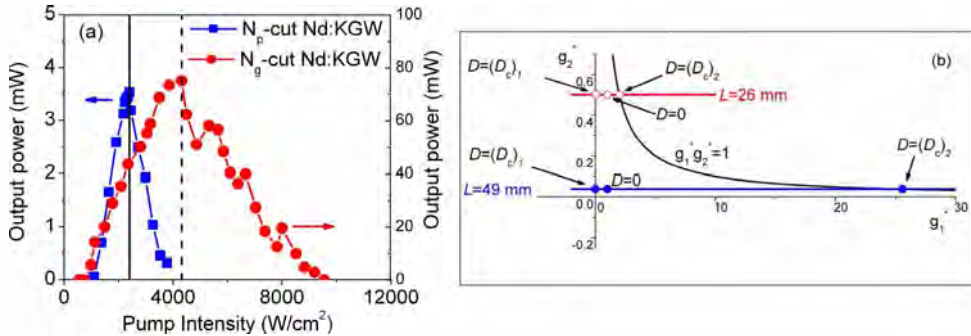

Fig. 3. (a) Measured output power as a function of the pump intensity $(P_p/\pi w_p^2)$ for N_p-(squares) and N_g- (circles) cut Nd:KGW lasers for a resonator length of $L = 49$ mm and with $L = 26$ mm respectively. Solid and dashed vertical lines indicate the critical pump intensity $(P_p/\pi w_p^2)_c$, above which the output power drops, for Np- and Ng-cut Nd:KGW, respectively. The laser resonators progress along the horizontal lines through the equivalent stability diagram (b) as the absolute value of the refractive power $|D|$ of the thermal lens in the active element increases. $(D_c)_1$ and $(D_c)_2$ are then the characteristic refractive powers at which the resonators intersects the stability limits.

Here, the output power increases with increasing pump intensity up to a certain critical value, $(P_p/\pi w_p^2)_c$, above which the output power abruptly drops. This value of $(P_p/\pi w_p^2)_c$ is equal to ≈ 2.4 kW/cm^2 and ≈ 4.3 kW/cm^2 for the N_p-cut and N_g-cut Nd:KGW lasers, respectively. According to [22], such a feature in the output power behaviour is observed when the laser resonator, due to the thermal lens induced in the active element, approaches the edge of stability region. Calculations in [22] show that, for the resonator configuration used in the experiment, there are two critical values of the thermal lens refractive power $(D_c)_1 = 1/(L-l + ln^{-1})$ and $(D_c)_2 = -1/(R-(L-l + ln^{-1}))$ (where L is the cavity length, l is the gain medium length, and n is the index of refraction of the gain medium) at which the laser resonator intersects the stability limits (Fig. 3(b)). For the N_p-cut Nd:KGW laser, $(D_c)_1 = 20.8$ dptr and $(D_c)_2 = -511.6$ dptr (the refractive index of Nd:KGW for the light polarization along the N_m-axis is $n = 2.01$ [25]). Comparing $(D_c)_1$ with $(D_c)_2$ yields the relation $|(D_c)_1|<<|(D_c)_2|$, and the abrupt drop in the output power for the N_p-cut Nd:KGW laser can be related to the focusing thermal lens as the critical value $(D_c)_1$ will be reached at lower pump intensity compared with the critical value $(D_c)_2$ of the defocusing thermal lens. Therefore, the sensitivity factor can be found to be $(M_{Np-cut})_{Nm} = (D_c)_1/(P_p/\pi w_p^2)_c = 0.87 \times 10^{-2}$ dptr/(W/cm^2). For the N_g-cut Nd:KGW laser, $(D_c)_1 = 39.9$ dptr and $(D_c)_2 = -40.1$ dptr. Because the N_g-cut Nd:KGW crystals possesses a focusing thermal lens, the sensitivity factor can be found to be $(M_{Ng-cut}) = (D_c)_1/(P_p/\pi w_p^2)_c = 0.92 \times 10^{-2}$ dptr/(W/cm^2). However, it is not possible to assign this value of M to a certain (N_m or N_g) direction.

It should be noted that the difference in the slope efficiencies of the two lasers does not influence the measurements of the thermal lens since the critical pump intensity depends only on the resonator parameters.

In Table 1 a summary of the results obtained for the thermal lensing sensitivity factors M and for the degree of astigmatism for the N_p-cut and N_g-cut Nd:KGW crystals are given. As can be seen from Table 1, the M-values for the N_p- and N_g-cut Nd:KGW obtained by the two

methods are in close agreement. Also it is clear that the N_p-cut Nd:KGW possesses a thermal lens having strong astigmatism with the degree of 2.85 dptr/(W/cm^2). The ratio of the M-factors for N_m- and N_g-directions, $(M_{Np-cut})_{Nm}/(M_{Np-cut})_{Ng}$, equals -0.425. The refractive powers of thermal lens for the N_g- and N_m-directions have different sign, minus and plus, respectively. In contrast, the thermal lens in the N_g-cut Nd:KGW displays weak astigmatism with the degree of 0.35 dptr/(W/cm^2), and the value of $(M_{Ng-cut})_{Nm}/(M_{Ng-cut})_{Np}$ here is found to be 1.4. This implies that the N_g-cut Nd:KGW laser, as compared to the N_p-cut Nd:KGW one, can operate at significantly higher pump intensities.

Table 1. Comparison of the thermal lensing sensitivity factors M and thermal lens' degree of astigmatism for the N_p-cut and N_g-cut Nd:KGW crystals. The factor M is deduced with two different methods, namely: (i) analysis of the laser output beam size in dependence on the distance from the output coupler at different pump intensity; and (ii) analysis of the laser output power as a function of the pump intensity.

Direction	M, dptr/(W/cm^2)			
	N_p-cut Nd:KGW		N_g-cut Nd:KGW	
	(i)	(ii)	(i)	(ii)
along N_m	0.85×10^{-2}	0.87×10^{-2}	1.2×10^{-2}	0.92×10^{-2}
along N_p	–	–	0.85×10^{-2}	
along N_g	-2.0×10^{-2}	–	–	–
Degree of astigmatism, dptr/(W/cm^2)	2.85		0.35	

In support of this statement it was observed in our experiments that the 7at.%-doped N_p-cut Nd:KGW laser could not operate in the cw regime, and laser oscillation was only obtained under quasi-cw pumping. In contrast, the 7at.%-doped N_g-cut Nd:KGW laser easily demonstrated cw oscillation with the same cavity configuration. It should be noted that the characteristics of the thermal lens in the N_g- and N_p-cut diode-pumped Nd:KGW crystals obtained here are in good agreement with the results of thermal lens studies in N_g- and N_p-cut Nd:KGW crystals under flashlamp-pumping at a wavelength of 1.067 µm [16]. Moreover, results of our measurements of the thermal lens in N_g-cut Nd:KGW are also consistent with the observations of the thermal lens in Yb:KGW crystal cut along the same direction [17]. Positive values of the thermal lens in vertical and horizontal directions (unfortunately, these directions were not assigned with the direction of polarization of the laser emission) were reported for this crystal [17]. Results in [11] on the thermal lens measurements in the N_p-cut Nd:KGW demonstrated strong negative thermal lens in the plane of polarization and the positive one in the perpendicular plane. These observations (regarding the sign of the thermal lens) are in contrast to the one made in [16] and in the present paper. Currently we cannot explain such discrepancy in the signs of the thermal lens.

Several factors contribute thermal lensing effect in the solid-state lasers: temperature- and stress-dependent variations of refractive index, bowling of the crystal faces under thermal expansion [18], specific diode beam profiles and collimation optics [17]. Thermo-optic coefficient dn/dT is the more significant among them especially in diode-pumped lasers [18]. Therefore, one can compare thermal lens sign with the one of dn/dT coefficient for the laser polarization (in our experiment it is parallel to the N_m-axis for both crystals). Our results on thermal lens signs are in correlation with [13], where dependence of dn/dT coefficient on the beam propagation direction was observed, with the negative value for light propagation along the N_p-axis and positive value for light propagation along the N_g-axis for light polarization along N_m-axis at 1.06 µm; and [14], where dn/dT coefficient (at 435.8 and 632.8 nm) for light polarization along N_g-axis was found to be negative while the two other values for light polarizations along N_p and N_m axes were positive [14].

We suppose that the laser performance of Nd:KGW crystal under diode pumping can be improved by cutting the crystal along some directions in the N_p-N_g plane for which thermal lens would be positive or close to zero with a weak astigmatism resulting in near-symmetric output beam.

4 Conclusion

A comparative study of the thermal lensing in diode laser pumped N_g- and N_p-cut Nd:KGW laser crystals was performed for laser emission polarized along the principle refractive axis N_m. The thermal lens in N_g-cut Nd:KG was found to have a weak astigmatism with positive refractive power for both the N_m- and N_p-directions. In contrast, the thermal lens in N_p-cut Nd:KGW possesses strong astigmatism with refractive powers of different signs for the N_g- and N_m-directions. The degree of astigmatism was found to be considerably weaker for the N_g-cut Nd:KGW in comparison with the N_p-cut one: 0.35 dptr/(W/cm^2) and 2.85 dptr/(W/cm^2), respectively. The factor M, the thermal lens sensitivity, for both configurations has also been studied and characterised. The ratios of the M-factors in the plane of polarisation and in the perpendicular plane were evaluated to be $(M_{Ng-cut})_{Nm}/(M_{Ng-cut})_{Np}$ = 1.4 and $(M_{Np-cut})_{Nm}/(M_{Np-cut})_{Ng}$ = −0.425 for the N_g- and N_p-cut Nd:KGW, respectively. Thus the 'athermal' N_g-cut crystal configuration shows significant promise specifically for diode-pumped 1.3 μm Nd:KGW lasers operating at high pump intensities.