

Thermo-optic effects in solid state lasers end-pumped by fiber coupled diodes

J.K. JABCZYŃSKI*, J. JAGUŚ, W. ŻENDZIAN, and J. KWIATKOWSKI

Institute of Optoelectronics, Military University of Technology, 2 Kaliskiego Str, 00-908 Warsaw

Review of thermo-optic effects in gain media of diode pumped lasers is presented. Methods of modelling and compensation of such effects are discussed. Results of characterization of end-pumped lasers by means of energetic and caustics measurement techniques are presented and discussed. Also application of Wigner distribution method for characterization of aberrated laser beams is discussed. Thermally induced astigmatism was observed for the anisotropic rods at high heat load.

Keywords: diode pumped solid state lasers, thermo-optics, laser beam characterization.

1. Introduction

Mitigation of thermal effects has been one of the most important scientific and technical challenges in almost every types of solid state lasers since advent of this type of a light source in the early 60'ties of last century [1,2]. Some new approaches and technical implementations have been proposed for diode pumped solid state lasers (DPSSL's), however, basically physics of the problem has remained the same. Typical routes of thermal effects control in DPSSL's can be divided into three groups:

- improvement in gain media technology,
- new designs of pumping schemes and resonators,
- improvement in cooling techniques.

The simplest way to lessen thermal effects is decrease in the heat deposited in a crystal, i.e., decrease in the quantum defect between pump and laser radiation. Very small quantum defect of a few percent was achieved lately for Yb doped media [3–4]. Moreover, applying laser cooling concept, complete vanishing of the deposited heat was experimentally demonstrated [5]. However, typical values of quantum defect (26% for Nd doped and about 10% for Yb doped media) state the lower fundamental limit in practice. As regards to the second group of techniques, it is still vital problem and basically each new laser requires special type of resonator enabling the compromise between energetic efficiency and beam quality. The last group of techniques includes traditional ones (conductive, liquid, thermoelectric cooling) and quite new as solid state heat pipes, high velocity gaseous or spray cooling methods. The important factors in these cases are increase in the cooling surface to gain volume ratio and minimization of temperature gradients across the beam. The best, from this point of view, are

double clad fibers [5] and thin disk concepts [6] leading to impressive progress in laser technology in last decade.

The goal of this work is to present the novel methods of characterization and mitigation of thermal effects in the DPSSL's. The review of thermal effects, examples of modelling, and partial compensation are presented in sec. 2. In sec. 3, the results of experimental characterization of end-pumped lasers are shown. The conclusions and future prospects are given in the last section.

2. Thermo-optic effects in DPSSL's

As it was mentioned earlier, basically each process of excitation in a gain medium results in deposition of heat inside it. The main difference in thermo-optics, characteristic for diode pumping, comparing to classical incoherent pumping techniques, is occurrence of 3D profiled heat source densities as a result of thin focusing volume of a pump beam and a limited value of absorption length. Thus, as a rule, strong transverse as well as longitudinal temperature gradients occur resulting in a complicated figure of thermally induced stress, deformations, and optical path differences (OPD). Moreover, because of a pumping method and a method of energy extraction out of the resonator, the instantaneous thermal and spectroscopic phenomena occur resulting in additional complication of the figure. Let us limit a scope of analysis to the stationary solution (from the thermodynamics point of view). Such a case is typical for cw pumped DPSSL's including also Q-switched regime. Further, we assume that inside the gain medium the stationary, 3D profile of temperature exists causing two the first-order thermo-optic effects: paraxial thermal lensing and thermally induced birefringence. The additional higher-orders thermally induced aberrations occur as a rule. Moreover, depending on a heat magnitude, several complex nonlinear effects can be observed as well.

* e-mail: jjabczynski@wat.edu.pl

2.1. Thermally induced birefringence and its compensation

The problem of thermally induced birefringence (TIB) was recognized several years ago in high power lamp pumped solid state lasers [1,2]. Its revitalization in the DPSSL's was caused by the need of harnessing of thermal effects in the most challenging diode pumped lasers, e.g., in quasi-three level lasers when linear polarization output is required. In such a case, diffraction losses can be dominated by TIB. Let us assume for simplicity that longitudinal gradients of temperature are neglected in comparison to transverse ones. In a stationary case, as a result of axial symmetric pump distribution and axial symmetric boundary conditions we have dealt with an axially symmetric transverse profile of temperature. However, the thermo-elasticity theory gives as a result a family of axially symmetric different solutions for radial and tangential components of stress [1,2,7]. The optical result is a TIB effect in such a case. The simplest way of TIB elimination is to use natural, highly anisotropic gain medium (e.g. Nd:YVO₄). However, in several cases such a method cannot be applied. A typical, well-established method to partly diminish L_d is application of a specially oriented waveplate [8–10]. The fast axis of this plate have to be aligned with polarization of an incidence field.

In the simplest case, such a role plays a $\lambda/4$ quarter-wave plate located between gain medium and rear mirror (Fig. 1). The role of waveplate consists in partial compensation of TIB phase shifts for azimuth angles inclined at $\pm 45^\circ$ with respect to the fast axis (Fig. 2). The feasibility of this compensation method was verified in our experiments (Fig. 3).

2.2. Thermally induced aberrations

For thermally induced deviations of a wavefront, the simple model of the first order thermal lensing is unsatisfactory for majority of DPSSL's. As a result of a confined pump intensity shape, the elongated heat source density occurs with a transverse profile of a Super-Gaussian shape. It results in a complicated figure of a wavefront with curva-

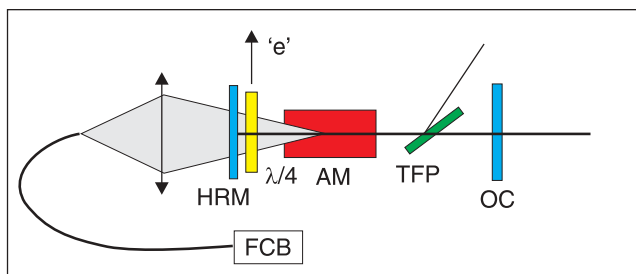


Fig. 1. Scheme of compensation of thermally induced birefringence: HRM – rear mirror high reflective at a laser wavelength, $\lambda/4$ – quarter-wave plate, AM – gain medium, TFP – polarizer, OC – output coupler mirror, and FCB – fiber coupled diode bar.

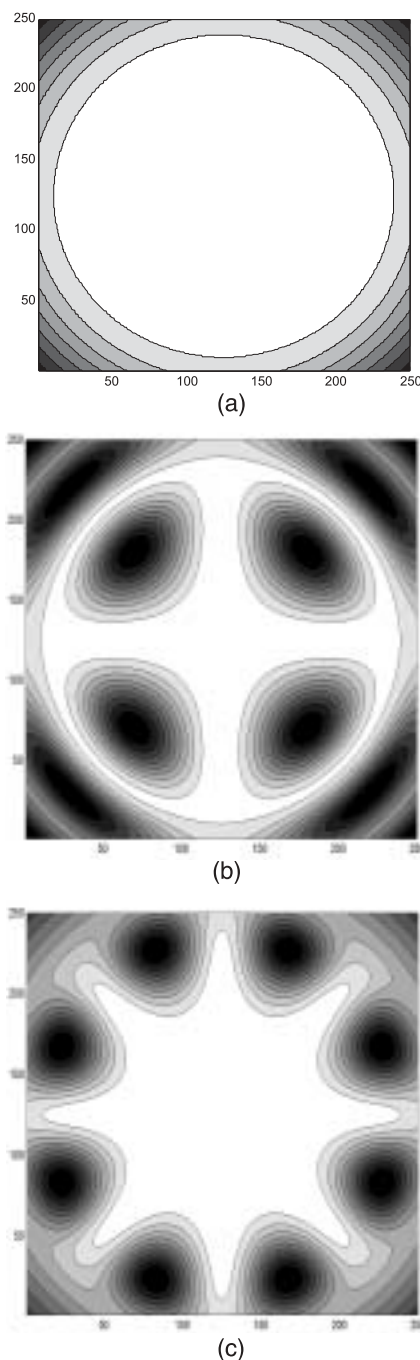


Fig. 2. Intensity map of output beam: without TIB (a), with TIB (b), with TIB and $\lambda/4$ waveplate (c).

ture radius increased with the distance to a centre. Two typical shapes of OPD's calculated for "top-hat" and Gaussian pumps are given in Fig. 4(a). The theoretical measure of a magnitude of thermally induced aberrations (TIA) can be defined as follows. Firstly, we have to determine effective thermal lensing optical power and remove the parabolic component of an aberrated wavefront. Further, we calculate the residual rms OPD over the beam averaged with respect to intensity profile. The value of it can be interpreted as a diffraction loss of Gaussian beam of a given profile experienced TIA during passing through the gain medium. The

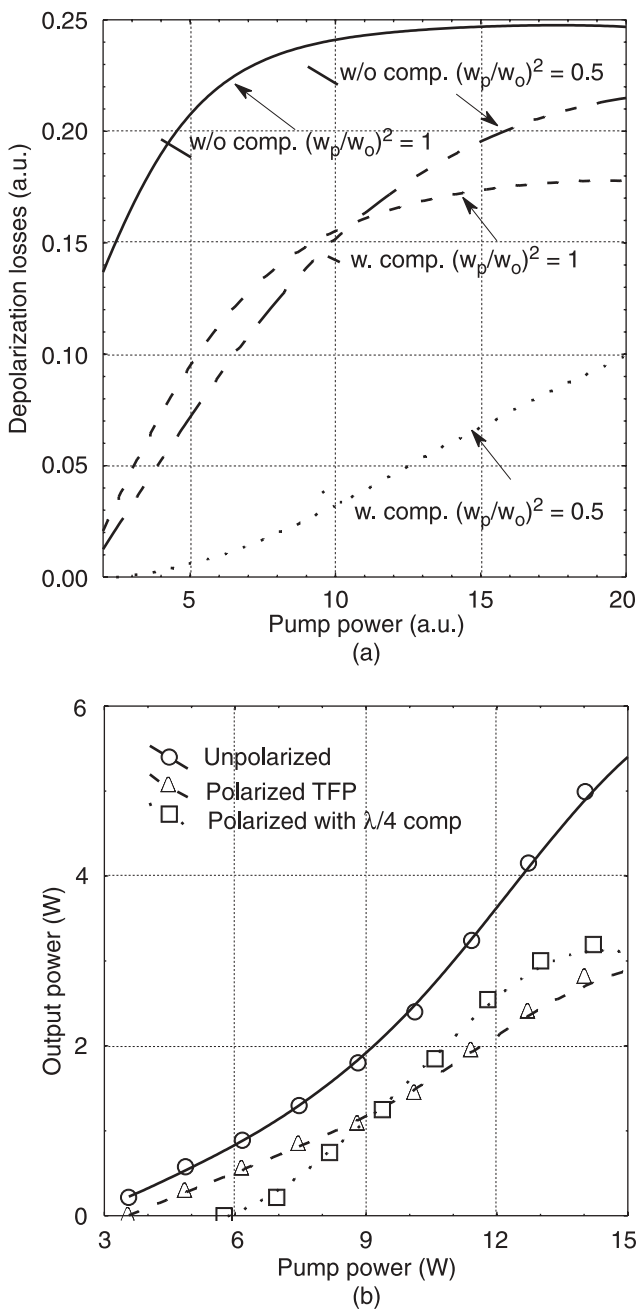


Fig. 3. Depolarization losses vs. pump power: results of simulation according to Ref. 8 (a); output power vs. pump power; Nd:YAG laser of 100-long cavity, unpolarized output circles, polarized by means of TFP (triangles), polarized with $\lambda/4$ compensation (squares) (b).

example of calculation of diffraction loss vs. pump power is given in Fig. 4(b). We have assumed here that the mode radius is equal to a pump beam one. For mode radius less than pump half width, the shape of a wavefront is dominated by the fourth order spherical aberration [8]. This conclusion is valid only for a very limited set of cases, because in lasers used in practice we have a divergent pump beam inside gain medium, moreover the bending and stress induced changes of OPD should be taken into account. Anyway, the effective optical power of thermally aberrated rod

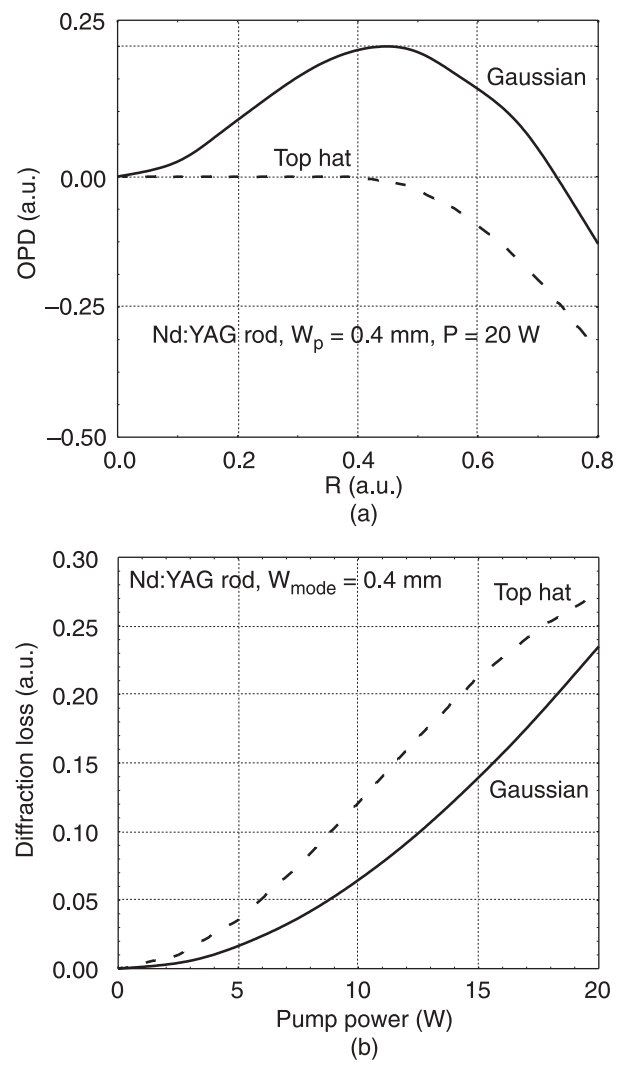


Fig. 4. OPD without parabolic term vs. radius: top hat pump (dashed), Gaussian pump (continuous), Nd:YAG rod, $W_p = 0.4$ mm, 20 W pump power (a); diffraction loss vs. pump power: top hat pump (dashed), Gaussian pump (continuous), Nd:YAG rod, $W_p = W_{mode} = 0.4$ mm (b).

and accompanying diffraction loss significantly depend on mode to pump radii ratio and magnitude and shape of pump radiation.

3. Characterization of thermo-optic effects in end pumped lasers

3.1. Wigner distribution method characterization of output beams of DPSSL's

In a process of designing and optimization of DPSSL, the trade off between the efficiency and beam quality of a laser has to be found. The strategy to achieve the highly efficient output with moderate beam quality was a subject of numerous work [8,10,12]. Despite a very severe TIA, it was found in practice that such lasers can generate near diffraction limited beams with $M^2 < 1.5$. It is not at variance with the results of sec. 2 because in a process of laser beam

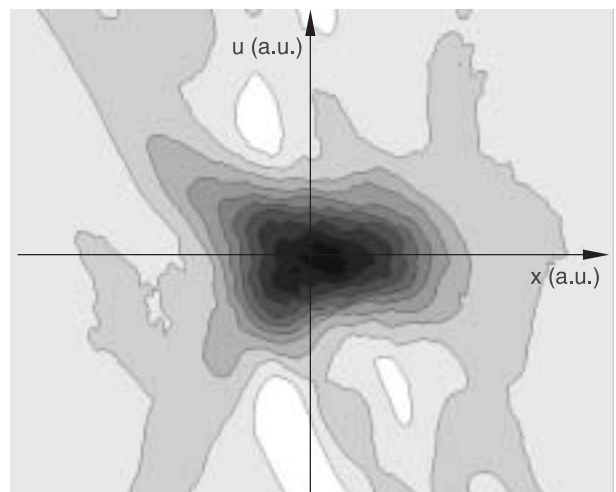
forming inside a cavity the “spatial cleaning” of mode occurs as a result of gain guiding and additional beam shaping mechanisms. The effective, “lowest losses” mode, only slightly resembles pure TEM₀₀ mode of bare cavity, and its spatial properties cannot be a priori predicted. Thus, the very important is quantitative characterization of output beam parameters of laser during its operation.

For such purposes we have prepared the experimental set up based at Wigner distribution method (WDM) [13–15]. The beam profiles were measured applying slit scan method with spatial resolution of 2.5 μm and 12-bit digitization. The post processing numerical procedure enabling calculations of beam parameters, Wigner transform, aberrations, and etc. was implemented in MATLAB 5.3. The details of the method and measurement set up are described in Ref. 16. This measurement procedure is valid only for stationary beams (i.e., spatial properties of a beam should be constant during the whole process of data acquisition) and fully axial symmetry is required. Main advantages of this method of beam characterization are the following:

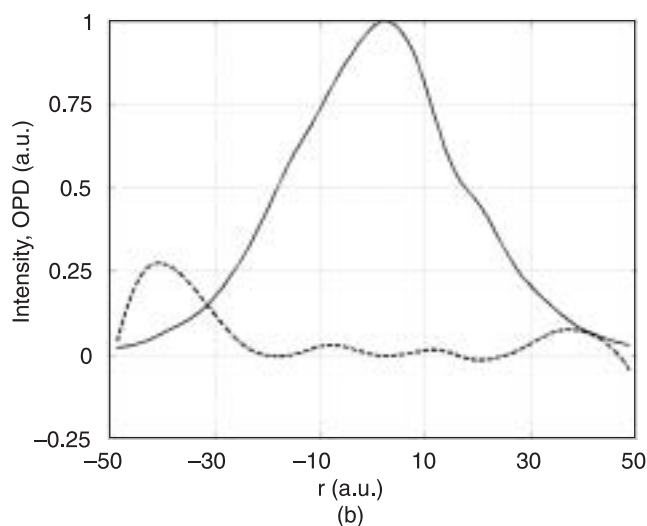
- direct access to beam parameters (waist size, divergence angles etc.),
- estimation of coherence degree and length,
- estimation of wavefront aberration of output beam,
- wide range of wavelength accessible,
- cw or pulsed mode of operation beams accessible.

Typical features of highly aberrated beam examined by means of WDM are shown in Fig. 5(a) and 5(b).

Despite quite severe heat load we have observed moderate increase in M^2 parameter (with the values not greater than 2) for each investigated laser due to spatial cleaning effect. Such, not large decrease in beam quality suggests that for pump beam parameters given in the experiments, TIA are dominated by the fourth order aberration, as it was suggested by Clarkson [8]. Moreover, it was experimentally verified that the spatial cleaning effect depends on the ratio of mode to pump widths and method of energy extraction out of the cavity. The energy transfer up conversion processes play an important role in forming the output beam and decide on the magnitude of effective optical power of the cavity [8]. The most intriguing effect, which we observed during numerous experiments on several types of DPSSL’s was the severe discrepancy between the beam parameters predicted using bare cavity ABCD approach and effective parameters of the output beams of the examined lasers. All the presented here results were obtained for the lasers with active elements made of highly natural anisotropic crystals (Nd:YVO₄, Nd:YAP), thus the effects of TIB can be neglected. Although Nd:YAP crystal has better thermo-optic properties comparing to vanadate one, the experimentally observed strength of thermo-optic effects in YAP was considerably higher comparing to the latter one [Fig. 6(a)]. Moreover, the output beam parameters were significantly influenced by a regime of laser generation. We have found that effective optical power of gain medium, being the relative measure of thermo-optic magni-



(a)



(b)

Fig. 5. Wigner distribution $F(x,u)$ of beam generated by Nd:YVO₄, with A-O q -switch: $I = 20$ A, $L_{rez} = 150$ mm, $M^2 = 1.46$, $Z_R = 99.9$ mm, horizontal axis x (a.u.), vertical axis, and frequency u (a.u.) (a); intensity in near field (continuous curve), wavefront aberration OPD (dashed curve) vs. r - the transverse coordinate (b).

tude depends on cavity length and type of energy extraction out of the cavity [Fig. 6(b)].

3.2. Effect of thermally induced astigmatism

For the higher heat loads we have observed the departure of axial symmetry, namely thermally induced astigmatism. It occurred for both gain media for cw and Q-switched regimes as well (see Fig. 7).

The origin of this effect is not fully understood and explained. We suppose that the reason may be the anisotropy of thermal conductivity and thermal dispersion of gain media. Thus, the assumption of fully axial symmetry with negligible thermally induced birefringence posed for Nd:YVO₄ and Nd:YAP laser cannot be fully satisfied for high heat loads.

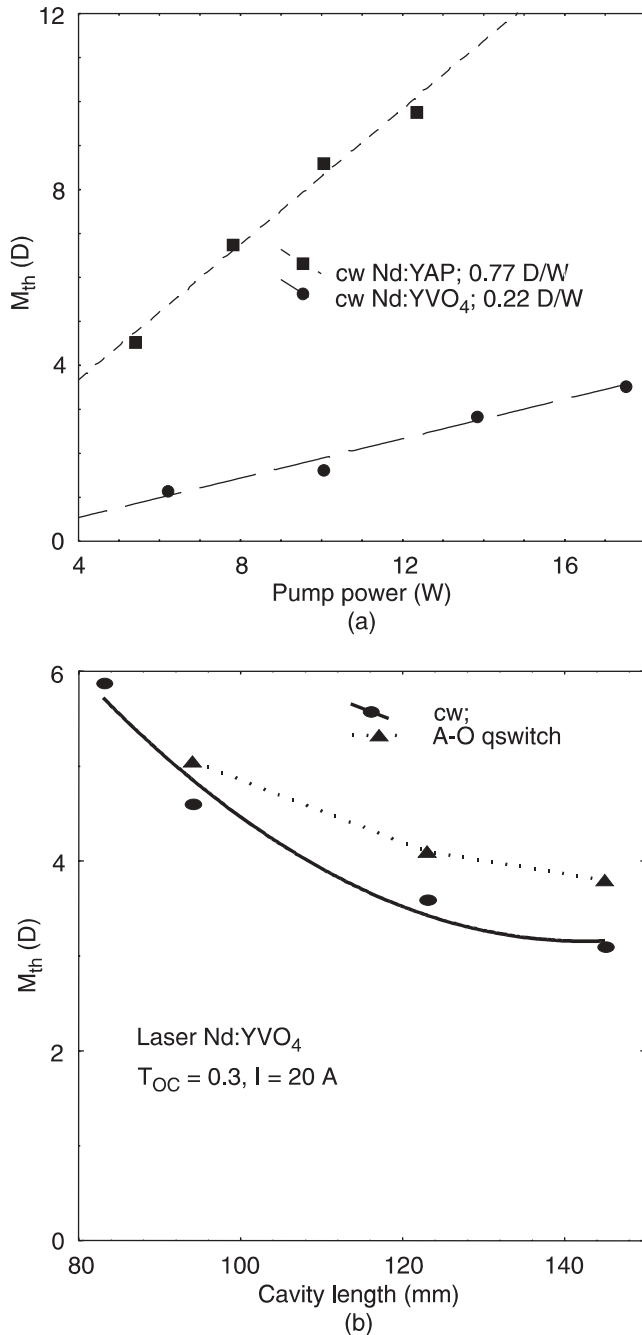


Fig. 6. Effective optical power of gain medium vs. pump power for Nd:YVO₄ (circles) and Nd:YAP (squares) lasers operating in cw regime (a); effective optical power of gain medium vs. cavity length for Nd:YVO₄ laser operating in cw (circles) and Q-switched (triangles) regimes (b).

4. Conclusions

The thermally induced birefringence can be substantially mitigated applying simple waveplates. The Wigner distribution method, implemented for estimations of the parameters of thermally aberrated beams of DPSSL's showed its feasibility. Modelling of thermo-optic effects evidenced the occurrence of high level of thermally induced aberrations



Fig. 7. Thermally induced astigmatic beam of passively Q-switched Nd:YVO₄ laser operating at 1340-nm wavelength, left hand picture – 20 mm before waist, middle picture in the waist, right hand picture 20 mm after the waist, and frame size 1.8 mm.

dominated by the fourth order component. The experiments, carried out on lasers with highly anisotropic media, showed that mechanism of spatial cleaning significantly reduces detrimental role of thermal aberrations. Moreover, it was experimentally verified that the spatial cleaning effect depends on the ratio of mode to pump widths and method of extraction of energy out of the cavity. The energy transfer up conversion process plays an important role in forming the output beam and decides on the magnitude of effective optical power of a cavity. Significant discrepancy between the beam parameters predicted using bare cavity ABCD approach and the effective parameters of the output beams of examined lasers were observed. Not fully understood effect of thermally induced astigmatism was observed in Nd:YVO₄, Nd:YAP lasers for high heat load and different regimes of operations. This effect can pose upper limit of pump power for such a type of lasers.

Acknowledgements

This work was supported by the Polish Committee for Scientific Research under the projects 4T11B02724, PBZ-MIN-009/T11/2003. We would like to thank Dr Z. Zawadzki for fruitful discussion on the results.

References

1. W. Koechner, *Solid State Laser Engineering*, 4th edition, Springer-Verlag, Berlin, 1996.
2. N. Hodgson and H. Weber, *Optical Resonators, Fundamentals, Advanced Concepts and Applications*, Springer-Verlag, Berlin, 1997.
3. P. Klopp, V. Petrov, U. Griebner, V. Nesterenko, V. Nikolov, M. Marinov, M.A. Bursukova, and M. Galan, "Continuous-wave lasing of a stoichiometric Yb laser material: KYb(WO₄)₂", *Opt. Lett.* **28**, 322–325 (2003).
4. S. Bowman, "Lasers without internal heat generation", *IEEE J. Quant. Electron.* **35**, 115–122 (1999).
5. L. Zenteno, "High-power double-clad fiber lasers", *IEEE J. Quant. Electron.* **11**, 1435–1446 (1993).
6. U. Brauch, A. Giesen, M. Karszewski, C. Stewen, and A. Voss, "Multiwatt diode pumped Yb:YAG thin disk laser

- continuously tunable between 1018 and 1053 nm”, *Opt. Lett.* **20**, 713–716 (1995).
7. A. Cousins, “Temperature and thermal stress scaling in finite length end-pumped laser rods”, *IEEE J. Quant. Electron.* **28**, 1057–1069 (1992).
 8. W.A. Clarkson, “Thermal effects and their mitigation in end-pumped solid-state lasers”, *J. Phys. D Appl. Phys.* **34**, 2381–2395 (2001).
 9. R. Hua, S. Wada, and H. Tashiro, “Principles and limitations of a quarter-wave plate for reducing the depolarization loss from thermally induced birefringence in Nd:YAG lasers”, *Opt. Comm.* **175**, 189–200 (2000).
 10. S. Seidel, A. Schirmacher, G. Mann, M. Nursianni, and T. Riesbeck, “Optimized resonators for high-average power, high-brightness Nd:YAG lasers with birefringence compensation”, *SPIE Proc.* **3267**, 214–225 (1998).
 11. J.K. Jabczyński, “Modelling of diode pumped laser with pump dependent diffraction loss”, *Opt. Comm.* **182**, 413–422 (2000).
 12. J. Bourderionnet, A. Brignon, J-P. Huignard, and R. Frey, “Influence of aberrations on fundamental mode of high power rod solid-state lasers,” *Opt. Comm.* **204**, 299–310 (2002).
 13. B. Eppich and N. Reng, “Measurement of the Wigner distribution function based on the inverse Radon transformation”, *Proc. SPIE* **2375**, 261–269 (1995).
 14. B.J. Neubert, *Measurements of the Wigner Distribution of Aberrated and Partially Coherent Laser Beams*, Cuvillier Verlag, Goettingen, 2004.
 15. J. Jaguś, J.K. Jabczyński, W. Żendzian, and J. Kwiatkowski, “Application of Wigner transform method for characterization of aberrated laser beams”, *Optica Applicata* to be published.
 16. J. Jaguś, *Theoretical and Experimental Analysis of Beam Emitted by Diode Pumped Laser under Thermal Abberation*, Master Thesis, Military University of Technology, Warsaw, 2004 (in Polish).