

Precise measurements of the thermo-optical aberrations of an Yb:YAG thin-disk laser

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Received April 17, 2013; revised June 10, 2013; accepted June 11, 2013;

posted June 12, 2013 (Doc. ID 188992); published July 5, 2013

We report on interferometric measurements of the thermo-optical aberrations of the laser medium of an Yb:YAG thin-disk laser in pumped and cw lasing conditions at several pump-power levels with a mean repeatability of 5 nm. These measurements build the basis for future intracavity compensation of the aberrations with our deformable mirror in order to improve the fundamental-mode efficiency. © 2013 Optical Society of America

OCIS codes: (140.3580) Lasers, solid-state; (140.3615) Lasers, ytterbium; (140.6810) Thermal effects.

<http://dx.doi.org/10.1364/OL.38.002422>

Solid-state lasers with high brightness $B = P_{\text{Laser}} / (\lambda \cdot M^2)^2$ [1] are of particular interest for materials processing. The brightness of a laser can be enhanced by increasing the output power P_{Laser} or by improving the beam quality (lower M^2 factor) at a given wavelength λ . In practice, increasing the brightness of high-power lasers is a difficult task, as improving the beam quality by suppressing higher-order modes usually comes at the cost of output power. Furthermore, the brightness is affected by thermo-optical aberrations of the laser medium resulting from a temperature difference between the pumped volume and the cooled surface. The thin-disk laser concept is well suited to minimize aberrations and, therefore, offers the potential for high brightness; nevertheless, aberrations are not negligible, especially for high pump power and fundamental-mode operation [2,3].

Thin-disk lasers utilize a thin laser-active disk that is quasi-end-pumped from the front and mounted with its back on a water-cooled heat sink [4]. This configuration allows for efficient and homogeneous cooling due to the large ratio of cooled surface to pumped volume and permits a nearly one-dimensional heat flow collinear to the laser beam axis [3]. The one-dimensional heat flow is beneficial for high brightness as the thermal effects (expansion of the disk and change of refractive index) caused by temperature distribution with isotherms running perpendicular to the laser beam do not distort its wavefront. However, a closer look at the temperature distribution shows that the isotherms run only perpendicular to the laser beam axis within the center of the pumped region of the disk and they are bent at the border to the unpumped region due to radial heat flow. This radial heat flow causes aspherical wavefront deformations of the beam that lead to diffraction losses and to a poorer beam quality. Moreover, the temperature difference between pumped volume and heat sink causes a mainly spherical bending of the disk. The wavefront will also be spherically deformed as it is reflected from the back of the disk. The spherical deformation can be compensated for by the resonator design and, hence, does not influence the brightness. Consequently, only the aspherical part of the wavefront deformation presents a true aberration.

The aspherical part of the thermo-optical aberrations has to be reduced in order to improve the brightness. This can be achieved, for instance, by using intracavity

adaptive optics. The design of adaptive optics suitable to compensate for aberrations first requires precise knowledge of their characteristics. Therefore, we carried out interferometric measurements of the thermo-optical aberrations of the laser medium with high resolution. To achieve the required measuring accuracy, we built our own phase-stepping interferometer. The wavelength of the interferometer should be close to the laser wavelength of 1030 nm due to the dispersion in Yb:YAG in order to measure the aberrations as they affect the laser beam. Furthermore, the measuring signal should not be absorbed or amplified by the laser medium. We decided to use 1064 nm as the measuring wavelength, which is close to the laser wavelength and at which the absorption and emission cross sections of Yb:YAG are already considerably smaller than at 1030 nm.

The measuring setup (see Fig. 1) consists of a phase-stepping Twyman–Green interferometer with a single frequency monolithic nonplanar ring oscillator (NPRO laser) [5] at 1064 nm (red line in Fig. 1), built in our laboratory, and a commercial thin-disk laser, manufactured by Trumpf GmbH & Co. KG. Its V-shaped resonator (blue line) with equal arm lengths of 520 mm consists of a plane highly reflective (HR) mirror and a plane output coupling (OC) mirror ($R = 95.5\%$), generating a multimode beam

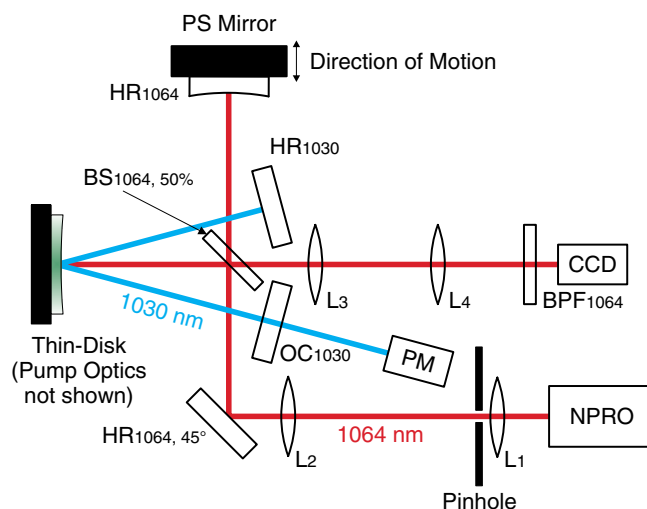


Fig. 1. Experimental setup to measure aberrations.

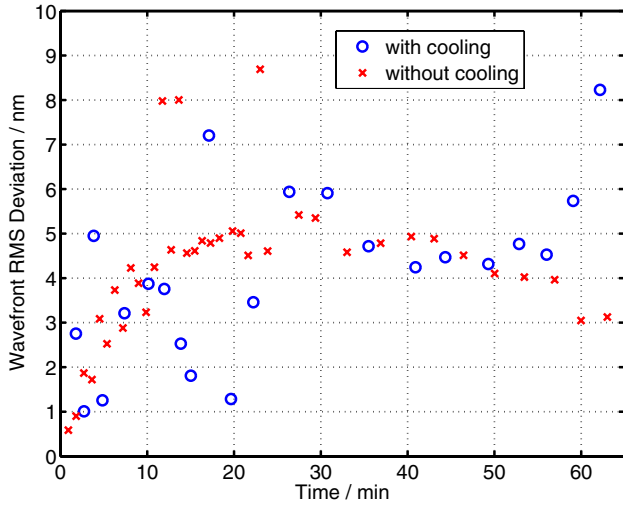


Fig. 2. Repeatability of the measurements in terms of RMS roughness. The mean repeatability is about 5 nm.

($M^2 \approx 20$) that impinges onto a powermeter (PM). The measuring laser beam (NPRO) passes a spatial filter (L_1 , pinhole) and a collimation lens (L_2) and is split by a 50% beam splitter (BS). One part of the split beam is guided to the thin disk and the other part to the phase-stepping (PS) mirror, both with 2 m radius of curvature. The thin disk, and with it the interferogram, is imaged via a telescope (L_3, L_4) onto a CCD camera. The bandpass filter (BPF) in front of the camera separates the NPRO laser from the fluorescent light of the pumped disk. This setup allows measurement of the aberrations of the pumped thin disk with and without laser oscillation.

While a measurement is performed, the PS mirror is shifted in steps of $\lambda/8$ in order to generate an optical path-length difference of the interferometer arms from 0 to λ . After each step, the interferogram is recorded by the camera. The phase-stepped images permit determination of the wavefront more exactly than would be

possible from a single interferogram [6]. A reference measurement is used to cancel out aberrations of the optics used and the initial deformation of the disk by subtracting a reference wavefront (unpumped disk) from each measurement of a series. With this method, the resulting wavefront can show a tilt because of the unavoidable creep effect of mirror holders during a measurement series. For this reason, the measured wavefront is fitted with Zernike polynomials in order to remove the piston, tip, and tilt terms. Subsequently, the wavefront is reconstructed from the remaining Zernike polynomials without piston, tip, and tilt. The reconstruction can act as a low-pass filter if the number of Zernike polynomials chosen is too small, and it can cause numerical errors if the number chosen is too large. We found that using 90 Zernike polynomials results in a sufficiently accurate reconstruction.

In the first step, we determined the accuracy of the interferometer. For this purpose, we carried out repeated measurements of the unpumped and uncooled as well as of the unpumped and water-cooled disk, each over a 1 h time period. The measured wavefronts should ideally be completely plane as they should be identical to the reference wavefront that was subtracted. To assess the deviation of the wavefronts from a planar surface with a single number, we calculated the RMS roughness of each measured wavefront. Figure 2 shows the repeatability of the measurements in terms of the RMS deviation, which is, on average, about 5 nm and in all cases below 9 nm. The reference was taken for both measurement series at time = 0 min in Fig. 2. The measured wavefronts show mainly a defocus in case of the uncooled disk, which may be caused by a slight change in ambient temperature during the 1 h measurement. In the case of the water-cooled disk, the deviation is dominated by the cooling-water temperature, which is controlled within 0.5°C by a two-point controller. Thus, the temperature fluctuations seem to be the limiting factor for the repeatability of our interferometer.

The measurements of the thermo-optical aberrations of the thin disk were carried out in a nitrogen atmosphere

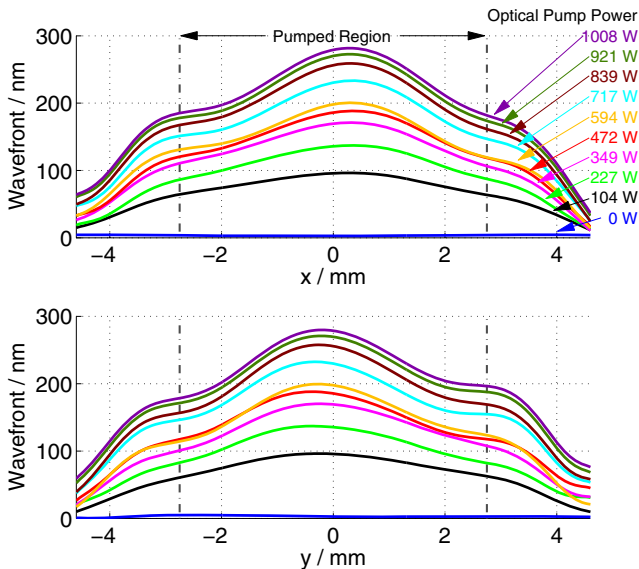


Fig. 3. Thermo-optical aberrations of the pumped thin disk with laser oscillation.

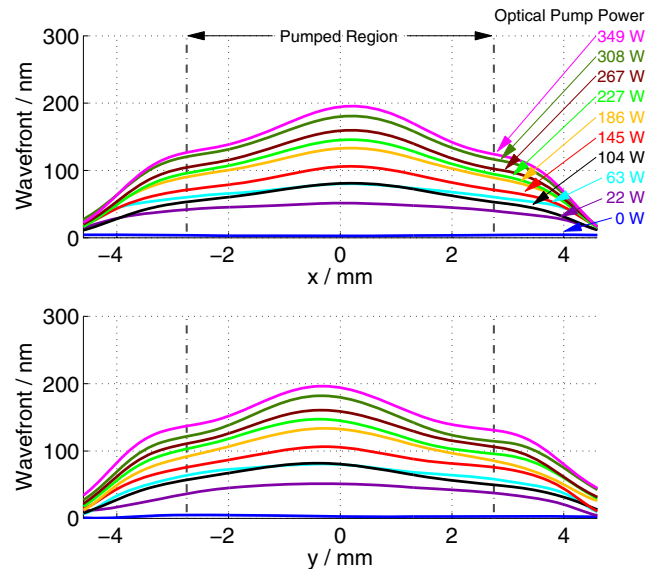


Fig. 4. Thermo-optical aberrations of the pumped thin disk without laser oscillation.

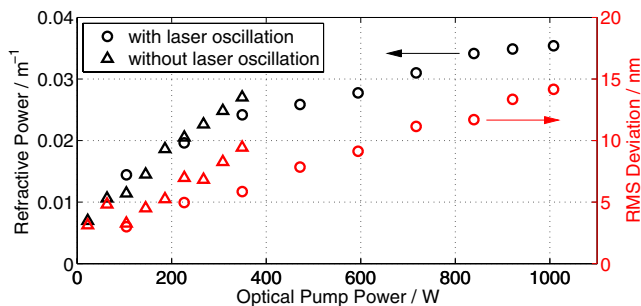


Fig. 5. Refractive power of the thin disk and higher-order RMS deviation depending on the optical pump power.

with and without laser oscillation at several pump-power levels up to a maximum optical pump power of 1 kW at 940 nm. In the case of the pumped disk, the above-mentioned fluctuating cooling-water temperature also affects the wavelength of the pump diodes. The wavelength of the pump diodes influences the amount of absorbed pump light and, therefore, the magnitude of the aberrations. Consequently, the repeatability of measurements of the pumped disk is reduced. To compensate for the fluctuating cooling-water temperature, each curve of the following figures represents an average of five measurements at the same pump power. Figure 3 shows cross sections of the aberrations in the x and y directions, measured with thin-disk laser oscillation. The aberrations have a spherical part within the pumped region as well as an aspherical part at the border of the unpumped region. The small asymmetry of the curves can have several causes, such as inhomogeneous pump-light distribution or inhomogeneous cooling of the disk. Figure 4 shows cross sections of the aberrations in the x and y directions, measured without thin-disk laser oscillation. In this case, the optical pump power was limited to a maximum of about 350 W to avoid destruction of the thin disk. The shape of the aberrations is similar with and without laser oscillation, but without laser oscillation the magnitude is slightly higher, which is mainly caused by the different polarizability of the ground and the excited states [7]. Measurements at the same pump power below the laser threshold of about 120 W pump power should be identical as the number of excited ions is equal in this case. Figure 5 shows the refractive power of the thin disk,

calculated from the defocus term of the Zernike fit, and the RMS deviation from a planar surface, calculated from the remaining terms without defocus, depending on the optical pump power. The spherical and aspherical parts of the aberrations increase in nearly linear fashion with the pump power in both cases, but the slopes are higher without laser oscillation.

To the best of our knowledge, our measurements of the thermo-optical aberrations are the first pump-power-dependent measurements and the most precise ones published so far. Moreover, they show good accordance to previously published simulations [2] and measurements [4,8]. The aim of our work is to increase the efficiency of fundamental-mode thin-disk lasers by means of our newly developed deformable mirror [9]. The precise measurements of the thermo-optical aberrations will allow us to adapt the mirror design so that it is ideally suited to compensate for these aberrations. Once this is finished, we will try to compensate for the aberrations in the future by the intracavity use of the deformable mirror.

We gratefully acknowledge the support of the German Federal Ministry of Education and Research under contract number 13N10631 and of Trumpf GmbH & Co. KG.

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