Thin-disk laser – Power scaling to the kW regime in fundamental mode operation

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ABSTRACT

A significant reduction of the influence of the thermal lens in thin-disk lasers in high power laser operation mode could be achieved, using dynamically stable resonators. For designing the resonator, investigations of thermally induced phase distortions of thin-disks as well as numerical simulations of the field distribution in the resonator were performed. This characterization was combined with thermo-mechanical computations.

On the basis of these studies, about 500 W output power with an averaged $M^2 = 1.55$ could be demonstrated, using one disk. Almost 1 kW output power with good beam quality could be extracted, using two disks. For the purpose of further power scaling in nearly fundamental mode operation, experiments using more than two disks are in preparation.

Keywords: thin-disk laser, thermal lensing, optical phase difference, power scalability

1. INTRODUCTION

Power scalability and minimal thermal lensing are the particular features of the thin-disk laser. High output power, high efficiency and good beam quality are further advantageous qualities of this type of solid-state lasers. Since the invention of the thin-disk laser 16 years ago [1], thin-disk lasers evolved to a common tool for cutting and welding. The highest published output power of an Yb:YAG single disk laser is 5.3 kW in multi-mode operation [2]. Nowadays, thin-disk lasers for material processing with an output power up to 16 kW, using four disks, are commercially available. These lasers operate typically in a high-order multi-mode ($M^2 \approx 20$).

Interest has been shifted towards a significant enhancement of the brightness. This would make new laser applications at long distances more practicable, especially in the fields of material processing as well as security and defense.

However, in the multi-kilowatt regime, thermal lensing is even in thin-disk lasers not negligible [3,4]. Therefore, a thin-disk laser resonator can be considered as a resonator containing an internal lens. Thermally induced phase distortions of the field distribution in the resonator can reduce the laser efficiency. Furthermore, these aberrations yield a degradation of the beam quality. This aspect is quite irrelevant in multi-mode operation. But in fundamental mode operation, it is necessary to reduce the influence of these aberrations or even to compensate for them, systematically. Dynamically stable resonators are well suited to reduce the influence of internal lenses [5 – 9]. Dynamically stable means that the radius of the laser mode in the active medium passes an extremum depending on the refractive power of an internal / thermal lens [10 – 12]. Near this extremum, a variation of the refractive power of the internal lens would yield only a very small variation of the mode structure.

Our goal is the experimental demonstration of concepts for *real* power scaling [13,14] of thin-disk lasers, especially in fundamental mode operation. Here, we present results of thin-disk characterizations as well as investigations of thin-disk lasers with dynamically stable resonators. An appropriate resonator design requires investigations of the refractive power and thermally induced aberrations of thin-disks. Besides this characterization, thermo-mechanical computations of disks as well as numerical simulations of the field distribution in the resonator were performed. On the basis of these studies, about 500 W of nearly diffraction limited output power could be demonstrated experimentally, using one disk. Almost 1 kW output power could be extracted with excellent beam quality, using two disks in a dynamically stable resonator. In order to enhance the brightness of thin-disk lasers operating in the multi-kilowatt regime, we intend to implement intracavity adaptive optics in further experiments.

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In the following sections, we describe the characterization of thin-disks and the implementation of thin-disk lasers with dynamically stable resonators. The characterization includes the measurements of the refractive power of thin-disks, the measurements of the phase aberrations (optical path difference OPD) of the disks as well as the measurements of the pump power distribution. With reference to these investigations, the results of simulations of the field distribution in dynamically stable laser resonators and thermo-mechanical computations of the disks are presented. Subsequently, dynamically stable thin-disk laser resonators containing one and two disks are described. Results of the laser performance are reported.

2. CHARACTERIZATION OF THIN-DISKS

For the purpose of the experimental realization of lasers with high brightness, the design of a dynamically stable resonator requires a thorough characterization of all components. A diagram of the performed characterization of thin-disk modules is displayed in Fig. 1.

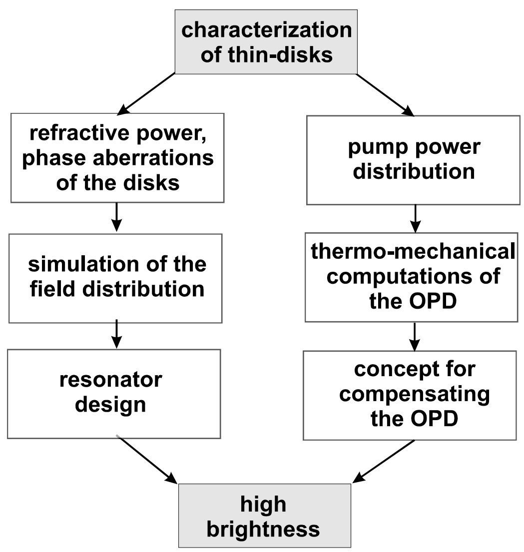

Fig. 1: Diagram of the characterization of thin-disks with respect to the enhancement of the brightness of thin-disk lasers.

Firstly, the refractive power, the aberrations as well as the pump power distribution are investigated. On the basis of these investigations, numerical simulations of the field distribution in the resonator are performed, in order to identify the influences of the aberrations on the beam quality. In combination with thermo-mechanical computations, the optical path differences (OPD) of the disks itself are analyzed, in order to improve alternative thin-disk designs. Based on these studies, the thin-disk laser resonators are designed and concepts for compensating the OPD are developed.

In order to demonstrate the power scalability of thin-disk lasers, Yb:YAG thin-disk laser modules with large pump spot radii (r_p = 4.15 mm), large disk radii (r_{disk} = 7 mm) and a maximum pump power P_p = 1.8 kW per module were used. The Yb:YAG thin-disks with a doping concentration of 12.5 % and a thickness of 140 µm are bonded on a 1.4 mm thick diamond substrate. The modules itself were manufactured by Trumpf Laser GmbH & Co. KG. The basic principle of thin-disk lasers is displayed in Fig. 2.

In the following, the characterization of thin-disk laser modules is described, including measurements of the refractive power and of optical path differences (OPD) as well as thermo-mechanical computations of the disks.

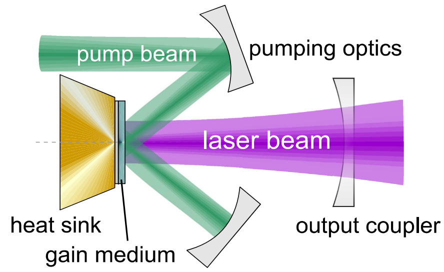

Fig. 2: Basic principle of the thin-disk laser: The gain medium is a thin crystalline disk, bounded on a heat sink. The rear side of the disk is HR coated for the laser wavelength as well as for the pump wavelength. The disk itself acts as a HR mirror of the laser resonator as well as a bending mirror for the pump beam. The pumping optics is designed for a multi-pass transit of the pump beam through the disk.

2.1 Refractive power of thin-disks

For adapting the stability range of the resonator to the variation of the radius of curvature of the disk, the refractive power of the disks was measured as function of the pump power in multi-mode operation (Fig. 3).

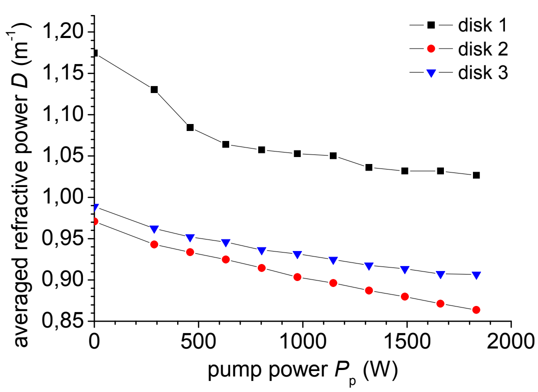

Fig. 3: Averaged refractive power D of three exemplary thin-disks as function of the pump power P_p in multi-mode laser operation.

The refractive power D of the disks shows a nearly linear decrease as function of the pump power P_p. This linearity is in accordance with predictions of thermo-mechanical computations [2].

The typical reduction of the refractive power is 7 - 15 cm^{-1} for a pump power up to 1.8 kW. At maximum pump power, the refractive powers of the disks are between 0.86 m^{-1} and 1.03 m^{-1}. Comparing the refractive powers along the x- and y-axis, there is also a slight astigmatism. The differences of these refractive powers are about 4 % of the maximum value. For designing the resonator, the minimum refractive power, i.e. maximum focal length, of the disks at maximum pump power, was taken as an upper limit of the thermal lens.

2.2 Optical path difference

The quantum defect in fluorescence processes, stimulated emission as well as amplified spontaneous emission (ASE) processes yield an increase of the temperature of the disk with increasing pump power. The resulting increase of the refractive index, the thermal expansion as well as the deformation of the disk are equivalent to a variation of the optical path difference (OPD) which is important for the field distribution in the resonator. Experimental as well as theoretical investigations of the OPD of thin-disks have been reported in the literature [3,14]. In order to develop concepts for the compensation of phase distortions as well as for an improvement of alternative designs of disk-bonding, OPD measurements have been performed.

The total OPD of a thin-disk can be considered as a sum of a parabolic part and a remaining non-parabolic part. Deviations of the OPD from the ideal parabolic shape cause phase distortions of the field distribution. The parabolic part of the OPD can be simply compensated by a variation of the resonator parameters, e.g. varying the radius of curvature of a mirror or varying the resonator length.

The deviations of the OPD and thus the phase distortions depend very sensitively on the homogeneity of the intensity distribution of the pump radiation [15]. They can yield a reduction of the optical efficiency in fundamental mode operation and a degradation of the beam quality due to an admixture of higher order modes. In order to investigate the deviations of the OPD from the ideal shape, measurements of the OPD with a Shack-Hartmann sensor were performed. The experimental setup is shown in Fig. 4.

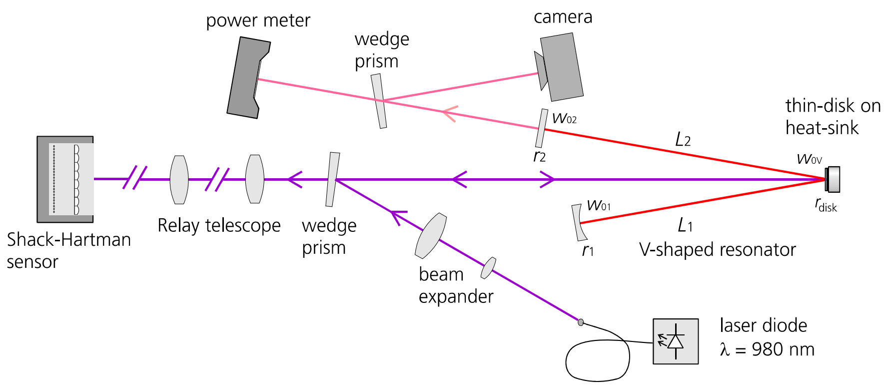

Fig. 4: Experimental setup for measurements of the optical path difference (OPD). The investigated disk is irradiated by a collimated probe beam (λ = 980 nm). The wavefront in the plane of the thin-disk is imaged on a Shack-Hartmann wavefront sensor, using a Relay telescope. The beam diagnostics include the detection of the laser output power and the beam profile. The measurements of the OPD were performed in laser operation mode (fundamental or multi-mode operation) as well as in fluorescence operation mode.

The measurements of the OPD were performed in laser operation mode (optional multi-mode or fundamental mode operation) as well as in fluorescence operation mode. The investigated disks show qualitatively similar OPDs in both operation modes. The results of a measurement of the OPD of one typical disk are shown in Fig. 5 and Fig. 6.

The OPDs of the investigated thin-disks show deviations from the ideal parabolic shape, depending on the pump power. Besides astigmatism, there is a radial increase of the deviations. The diagrams of the OPD show a good agreement with the subtracted paraboloid within the pump spot (r_p = 4.15 mm). In this area of the disk, the optical path differences are smaller than 100 nm.

To allow for fundamental mode operation, the radius w_{0V} of the laser mode on the disk has to be about 70 % of the pump spot radius r_p. Therefore, an important criterion for fundamental mode operation is the degree of the deviations of the OPD within the radius of the laser mode on the disk. For compensating these deviations, the utilization of intracavity adaptive optics would be useful. If the spatial resolution of the deformability of an adaptive optical element is high enough, this could be also used to compensate for the non-parabolic part of the OPD.

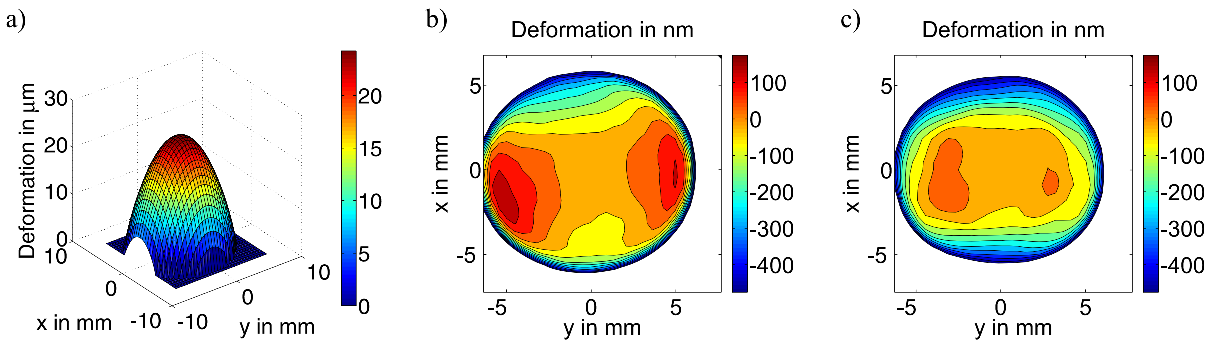

Fig. 5: Optical path difference (λ = 980 nm) of a typical disk in fundamental laser operation mode: a) total path difference with P_p = 1030 W; b) with P_p = 0 W after subtraction of an axially symmetric paraboloid $z = (x^2 + y^2)/(2r_{disk})$, with r_{disk} = 2.01 m; c) as b), but with P_p = 1030 W, r_{disk} = 2.19 m.

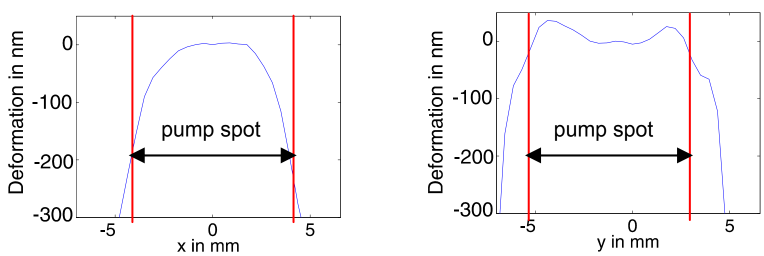

Fig. 6: Cross sections of the optical path differences in Fig. 5c along the x- and y-axis (pump power P_p = 1030 W, pump spot radius r_p = 4.15 mm, r_{disk} = 2.19 m).

2.3 Thermo-mechanical modeling of thin-disks

For the purpose of further optimization of the design of thin-disks laser modules, thermo-mechanical computations were performed, using a finite elements (FE) software. Especially to discriminate between the influence of inhomogeneous pumping and the influence of non-perfect mounting of the disk, we evaluated these path differences for an idealized design numerically. Fig. 7 shows the assumed mechanical setup: the thin-disk is bonded (e.g. glued) to a disk made of diamond, this diamond disk is hold in an annular copper structure. No initial curvature of the disk was assumed. The diamond is cooled from the bottom.

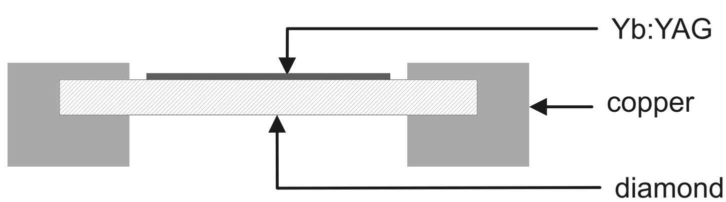

Fig. 7: Cross-section of the mechanical structure used for FEM calculations (not to scale).

To calculate the thermally induced stress and deformation inside the disk, we applied a volume heat source inside the disk. The heat distribution was calculated based on fluorescence measurements of a disk in double pass pump set-up. We assumed that this fluorescence is proportional to the pump power density distribution. We used numerical raytracing which accounts for the bleaching of the absorption to calculate the spatial distribution of the absorption in the disk with a 16 pass pump set-up. At 1 kW pump power we calculated an absorption efficiency of about 90 %. With a quantum defect of about 10 %, this generates about 90 W of heat inside the disk. For the distribution of this heat inside the disk, we assumed that the heat is generated proportionally to the previously calculated spatial distribution of the absorption. The resulting distribution of the heat inside the disk is sketched in Fig. 8.

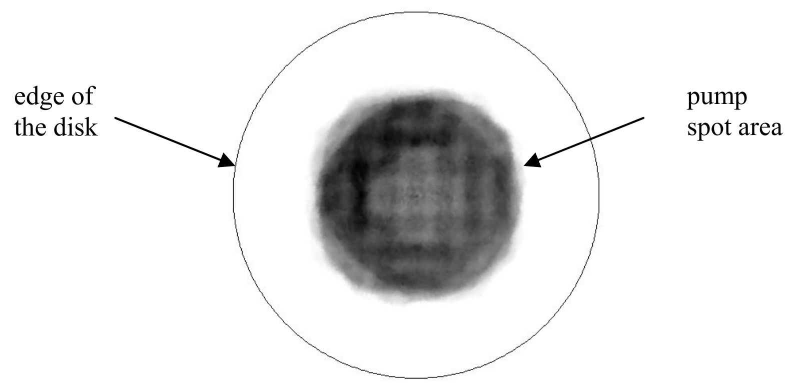

Fig. 8: Distribution of the heat source density in the disk, max. value about 18 kW/cm^3, 90 W total heat source (white = low density, black = high density).

From the results of the finite element software, the optical path difference (OPD) $\Phi(r)$ can be calculated by [14, 16, 17]:

$$\Phi(r) = 2\left[\int_0^{h_{\text{disk}}}\left[n_0 + \frac{\partial n}{\partial T}\left(T(r,z) - T_0\right) + \Delta n_s(r,z) - 1\right]\cdot\left[1 + \varepsilon_z(r,z)\right]dz - z_0(r)\right],$$

with n_0 the refractive index at the reference temperature T_0, $\partial n/\partial T$ the thermo-optical coefficient, Δn_s the change of refractive index due to stresses, ε_z the strain in z-direction and z_0 the displacement of the HR side of the disk, h_{disk} the thickness of the disk. A cross section of the resulting optical path difference is shown in Fig. 9.

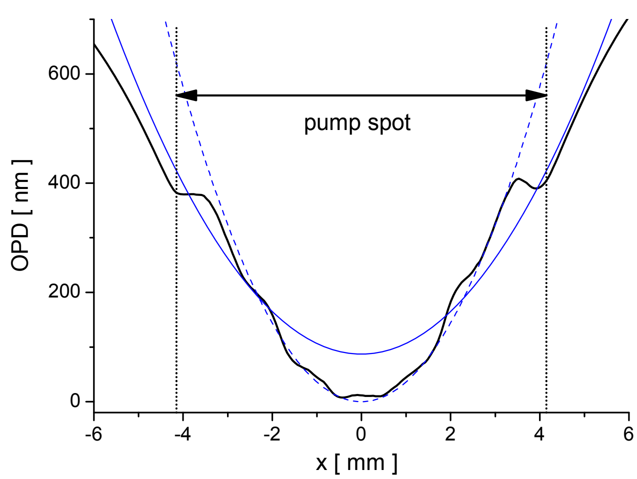

Fig. 9: Cross section of the calculated optical path difference (thick line: Total OPD, solid line: paraboloid with D = 3.9 cm^{-1}, dashed line: paraboloid with D = 7.2 cm^{-1}, pump spot radius r_p = 4.15 mm).

As the path difference has a mainly parabolic shape, it is useful to split it into two parts: a parabolic part, which can be expressed as an optical refraction power associated with the disk, and a remaining path difference, the so-called non-parabolic part of the thermal lens. Subtracting a parabolic phase (refractive power D = 3.9 cm^{-1}) yields the resulting non-parabolic OPD shown in Fig. 10. A cross section of this remaining optical path difference is depicted in Fig. 11, showing a variation of the path difference of about 200 nm across the pump spot. We can also assume a higher optical refraction power, as can be seen in, this will lead to a similar variation across the pump spot (and a stronger variation across the whole disk), but to a significantly reduced path difference inside a radius of 3 mm (less than 50 nm).

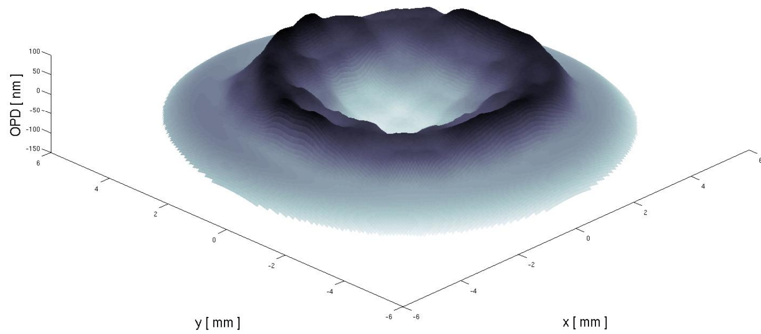

Fig. 10: Calculated optical path difference, corrected by 3.9 cm^{-1}

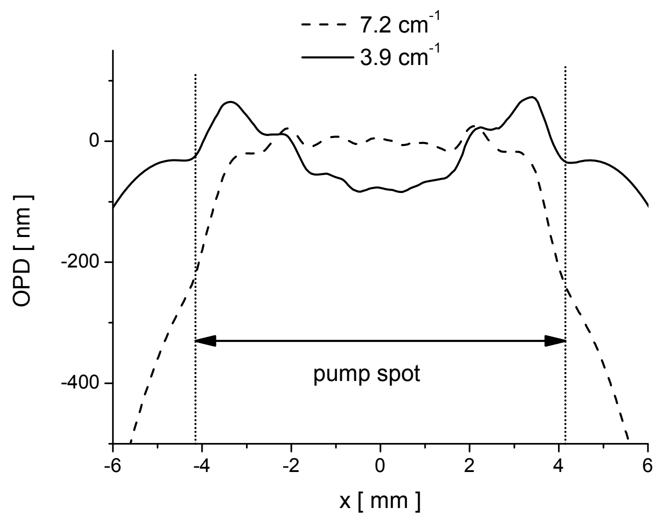

Fig. 11: Cross sections of the calculated optical path difference, corrected with different values of the optical refraction power (pump spot radius $r_p = 4.15$ mm).

In comparison with the measurements (Fig. 6), the thermo-mechanical modeling shows similar deviations from the parabolic shape. Depending on the refractive power of the subtracted axially symmetric paraboloid, the deviations of the OPD within the pump spot area of the disk are small (< 100 nm), but radially increasing for $r > r_p$. Subtracting suitable parabolids with smaller refractive power, the deviations of the OPD are in a range of ±100 nm over the whole disk (Fig. 11).

The measured astigmatism can not be explained by the assumed inhomogeneity of the pump power distribution. This may be due to the influence of the bonding or mounting process for real disks. The different results for the thermal lens can be explained by a different stiffness of the heat sink and/or the annular copper structure. Additionally, the adequate refractive power strongly varies with the aperture.

Characterizing thin-disks, the variation range of the refractive power as function of the pump power as well as the phase aberrations were determined. On the basis of these investigations, the resonator design is described in the next section.

3. THIN-DISK LASERS WITH DYNAMICALLY STABLE RESONATORS

As shown in the previous chapter, thermal lensing in thin-disk lasers is not negligible in the high power regime. Therefore, a thin-disk laser resonator can be considered as a resonator containing an internal focusing element. However, for fundamental mode operation, the radius of the laser mode has to be adapted to the radius of the pump spot and the resonator should be almost insensitive against thermal lensing. Dynamically stable resonators can combine these two features, simultaneously. A dynamically stable resonator is a special type of stable resonators. An ordinary dynamically stable resonator contains one internal lens between the two laser mirrors. Usually, dynamically stable resonators have two ranges of stability. Each range has a point of insensitivity of the mode radius to the variation of the refractive power of the internal lens. This has been extensively reported in the literature[10, 11, 12]. Here, we present our experimental results of the realization of dynamically stable resonators containing one and two disks. The development of concepts for the implementation of more than two disks in one resonator is in preparation.

3.1 V-shaped resonator with one disk

A simple dynamically stable thin-disk laser resonator is a V-shaped resonator containing one thin-disk module (Fig. 12).

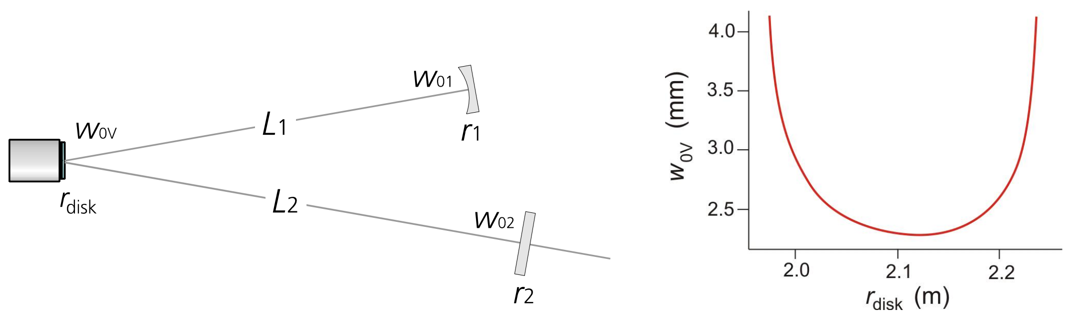

Fig. 12: Left: Dynamically stable V-shaped resonator with one thin-disk as bending mirror ($L_1 = 2.305$ m, $L_2 = 2.198$ m; mirror radii: $r_1 = 0.5$ m, $r_2 = \infty$, curvature radius of the disk $r_{disk} \in$ [2.0 m; 2.22 m]; calculated beam radii of TEM_{00} on the mirrors, on the disk: $w_{01} = 0.285$ mm, $w_{02} = 0.254$ mm, $w_{0V} = 2.843$ mm; pump spot radius $r_p = 4.15$ mm; reflectivity of the output coupler $R = 0.96$). Right: Calculated beam radius w_{0V} of TEM_{00} on the disk as function of the curvature radius of the disk r_{disk}.

Due to the reabsorption in the unpumped area of the thin-disk, the pump spot acts as a soft aperture. For small mode radii w_{0V} of TEM_{00}, higher order laser moder can oscillate. By increasing w_{0V} these higher order modes can be suppressed effectively. If w_{0V} gets too large the losses of TEM_{00} increase too. An optimum for fundamental mode operation is reached for $w_{0V} \approx 0.7 r_p$.

According to the resonator configuration in Fig. 12, the TEM_{00} mode radius w_{0V} passes a minimum with increasing radius of curvature of the disk r_{disk}. If laser operation is provided near the minimum ($r_{disk} \approx 2.12$ m), the mode radius on the disk gets almost independent of the pump power. Classically, one would set the operating point at maximum pump power near to this minimum to reduce the influence of the thermal lens. Instead, we used a resonator design where this minimum is reached at medium pump power and the optimum ratio w_{0V}/r_p is reached at maximum pump power.

For the values of the mirror radii of curvature r_i as well as the propagations lengths L_i in Fig. 12, the stability range fits very well to the variation range of r_{disk}, i.e. to the variation range of the pump power P_p. For $r_{disk} = 2.0$ m at $P_p = 0$ W the TEM_{00} mode radius w_{0V} is about 3 mm = $0.7 r_p$ (pump spot radius $r_p = 4.15$ mm), just like for $r_{disk} = 2.2$ m at $P_p \approx 1.4$ kW. For these values of r_{disk}, fundamental mode operation can be obtained. For values between these two limits of r_{disk}, there is an admixture of higher order modes to the fundamental mode.

In our experiments, the laser emission starts in TEM_{00} mode operation at the threshold, changes continuously to a mixture of higher order laser modes with increasing pump power and then, after w_{0V} passing the minimum value, the mode structure turns back to the fundamental mode (Fig. 13). This is confirmed by numerical simulations of the far field as well as the field distribution inside the resonator, considering real pump power distributions on the disk. In this way, we could demonstrate fundamental mode operation of a dynamically stable resonator with one disk, with a maximum output power P_{out} = 496 W (pump power P_p = 1367 W) and with an optical efficiency η = 0.362 (Fig. 14).

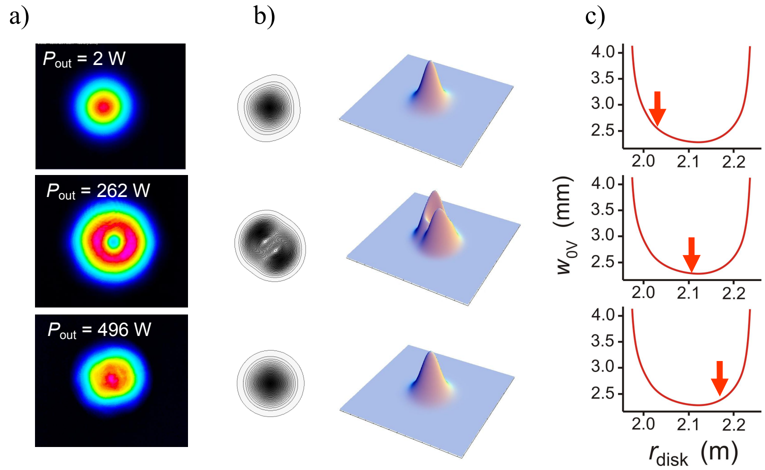

Fig. 13: a) Measured laser mode profiles at P_{out} = 2 W, 262 W and 496 W. b) Contour plots and 3D graphics of the numerical simulations of the field distribution in the far field. c) Radius of TEM_{00} on the disk as function of the radius of curvature r_{disk} of the disk. The arrows indicate the radius of curvature of the disk at the corresponding output power. For r_{disk} = 2.22 m, the optimal ratio of fundamental mode radius to pump spot radius is fulfilled (w_{0V} / $r_p \approx 0.7$).

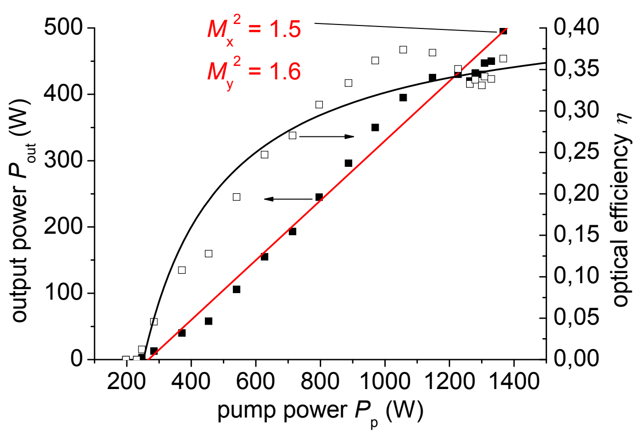

Fig. 14: Output power P_{out} and optical efficiency η of the dynamically stable V-shaped resonator with one disk as function of the pump power P_p. The maximum output power in fundamental mode operation was P_{out} = 496 W with an optical efficiency of η = 0.362 and with M_x^2 = 1.47, M_y^2 = 1.63 (measured with Data Ray WinCam D).

3.2 W-shaped resonator with two disks

In this section, we present the results of our experiments with a W-shaped resonator containing two thin-disks. This resonator may be regarded as a coupled assembly of two single V-shaped resonators. The plane output couplers of two V-shaped resonators are joined to one HR bending mirror, in order to "combine" the two resonators to one resonator (Fig. 15).

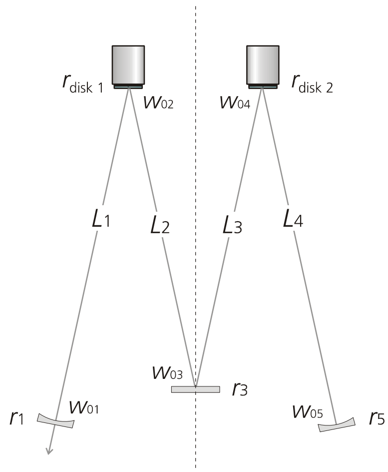

Fig. 15: Experimental setup of a dynamically stable W-shaped resonator with two disks (L_1 = 2.305 m, L_2 = 2.198 m, L_3 = 2.116 m, L_4 = 2.250 m; mirror radii: r_1 = 0.5 m, $r_3 = \propto$, r_5 = 0.5 m; reflectivity of the output coupler R = 0.92; curvature radii of the thin-disks: $r_{\text{disk 1}} \in$ [2.00 m; 2.22 m], $r_{\text{disk 2}} \in$ [1.96 m; 2.16 m]; pump spot radii on both disks r_p = 4.15 mm).

Due to the slight difference of the refractive powers of the two thin-disks, the propagation lengths L_i of each V-shaped part of the W-shaped resonator have to be adjusted in order to get nearly identical mode radii w_{02} and w_{04} on both disks. As mentioned above, for fundamental mode operation a ratio of radii $w_{02,04} / r_p$ should be about 0.7. Using this resonator, we get nearly fundamental mode operation with a maximum output power P_{out} = 904 W with a pump power P_p = 2464 W. Disadvantageously, the heat generation in the disk induces turbulences in air, especially in front of the thin-disk. These turbulences yield fluctuations of the output power up to 5 % of its maximum value (Fig. 16). Compared to high-order multi-mode operation, there is a considerable reduction of the optical efficiency in fundamental mode operation due to the fluctuations of the refractive index of hot air.

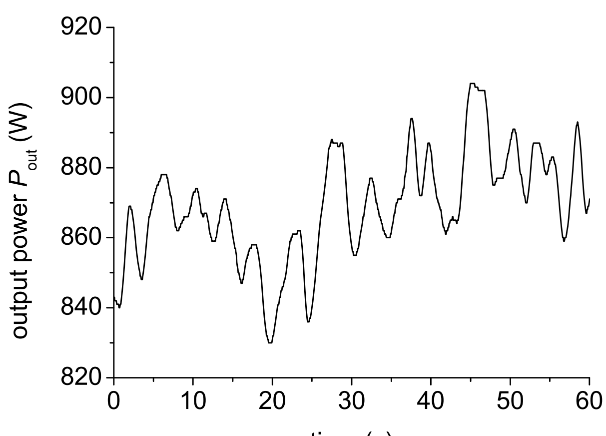

Fig. 16: Measured output power P_{out} as function of the time with slightly increasing pump power up to P_p = 2464 W.

Unfortunately, the turbulences in air were so strong that they inhibited the measurement of M^2 at this pump power. For this reason, we measured the beam profiles at P_{out} = 788 W (Fig. 17). For an output power P_{out} = 904 W the beam profiles were similar to these.

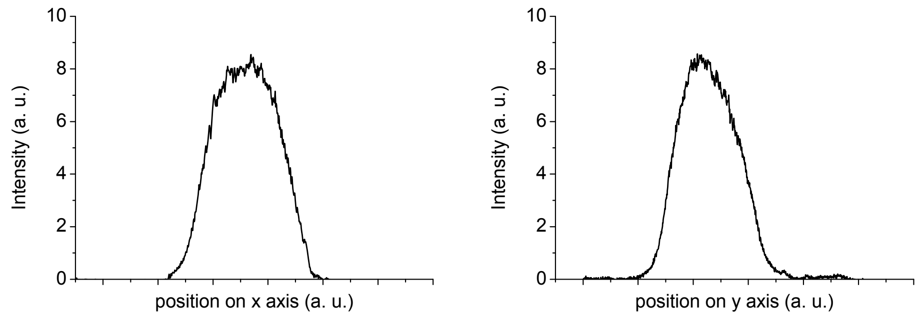

Fig. 17: Beam profiles along the x- and y-axis of the transverse plane of the thin-disk laser resonator as displayed in Fig. 15 (P_{out} = 788 W).

4. CONCLUSIONS

Thin-disks, bonded on a 1.4 mm diamond substrate, have been characterized by measuring the refractive power and the optical path difference (OPD) in laser operation mode. There was a typical linear decrease of the refractive power of about 10 % from 0 to 1.8 kW pump power. The deviations of the OPD from the ideal axially parabolic shape are typically 100 nm within the pump spot and up to 400 nm at the edge of the disk. Thermo-mechanical computations show good agreements with these experimental results.

In order to demonstrate high output power of thin-disk lasers in fundamental mode operation, dynamically stable resonators were used. For designing these resonators, simulations of the internal field distribution were performed. An output power of 500 W with one disk and almost 1 kW with two disks with good beam quality could be demonstrated.

These investigations are the basis for the development of concepts for the compensation of thermal lensing, using intracavity adaptive optics. Further experiments for the implementation of an arbitrary number of thin-disks in one resonator are in preparation.

REFERENCES

[1] A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, H. Opower, "Scalable concept for diode-pumped high-power solid-state lasers", Appl. Phys. B **58**, 365 – 372 (1994)

[2] A. Giesen and J. Speiser “Fifteen years of work on thin-disk lasers: results and scaling laws”, IEEE JSTQE **13(3)**, 598-609 (2007)

[3] U. Schiegg, “Untersuchungen zum Single-Frequency-Betrieb von Scheibenlasern bei höchsten Leistungen”, Diploma Thesis, University of Stuttgart (1997)

[4] K. Contag et al., “Theoretical modelling and experimental investigations of the diode-pumped thin disk Yb:YAG laser”, IEEE J. Quantum Electron. **29 (8)**, 697 (1999)

[5] J. Steffen, J. P. Lörtscher, G. Herziger, „Dynamic stable resonators: a design procedure“, IEEE J. Quant. Electron **QE-8**, 239 (1972)

[6] J. P. Lörtscher, J. Steffen, G. Herziger, „Dynamic stable resonators: a design procedure“, Optical and Quantum Electronics **7**, 505-514 (1975)

[7] P. H. Sarkies, “A stable YAG resonator yielding a beam of very low divergence and high output energy”, Optics Communications Vol. **31**, No. 2 (Nov. 1979)

[8] D. C. Hanna, C. G. Sawyers and M. A. Yuratich, “Large volume TEM_{00}-mode operation of Nd:YAG lasers”, Optics Communications Vol. **37**, No. 5 (Jun. 1981)

[9] D. C. Hanna, C. G. Sawyers and M. A. Yuratich, “Telescopic resonators for large-volume TEM_{00}-mode operation”, Optical and Quantum Electronics **13**, 493-507 (1981)

[10] V. Magni, "Resonators for solid-state lasers with large-volume fundamental mode and high alignment stability”, Applied Optics Vol. **25**, No. 1 (1986)

[11] S. De Silvestri, P. Laporta and V. Magni, "Misalignment sensitivity of solid-state laser resonators with thermal lensing”, Optics Communications, Vol. **59**, No. 1 (1986)

[12] V. Magni, "Multielement stable resonators containing a variable lens", JOSA A Vol. **4**, Nr. 10, 1962 (1987)

[13] R. Paschotta, "Power scalability as a precise concept for the evaluation of laser architectures," in CLEO/Europe and IQEC 2007 Conference Digest, (Optical Society of America, 2007), paper CA3_2

[14] J. Speiser, A. Giesen, “Scaling of thin-disk pulse amplifiers”, Proceedings of SPIE 6871, Photonics West 2008, 24 – 29 Jan. 2008

[15] J. Mende, J. Speiser, G. Spindler, W. L. Bohn, A. Giesen, “Mode dynamics and thermal lens effects of thin-disk lasers”, Proceedings of SPIE 6871, Photonics West 2008, 24 – 29 Jan. 2008

[16] K. Contag, “Modellierung und numerische Auslegung des Yb:YAG-Scheibenlasers” (Herbert Utz Verlag , München, (2002)

[17] J. Speiser and A. Giesen, “Numerical Modeling of High Power Continuous-Wave Yb:YAG Thin Disk Lasers, Scaling to 14 kW”, ASSP 2007, OSA Technical Digest Series, paper WB9 (2007)