$Yb:CaF_2$ thin-disk laser

Katrin Sarah Wentsch,[1,*] Birgit Weichelt,[1] Stefan Günster,[2] Frederic Druon,[3] Patrick Georges,[3] Marwan Abdou Ahmed,[1] and Thomas Graf[1]

[1]*Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*
[2]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*
[3]*Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris Sud 2, Avenue Augustin Fresnel, 91127 Palaiseau Cedex, France*
[*]*Katrin.Wentsch@ifsw.uni-stuttgart.de*

Abstract: We present Ytterbium-doped CaF_2 as a laser active material with good prospects for high-power operation in thin-disk laser configuration owing to its favorable thermal properties. Thanks to its broad emission bandwidth the material is also suitable for the generation of ultra-short pulses. The properties of the crystal as well as the challenges related to the coating, polishing, mounting and handling processes which are essential to achieve high power laser oscillation in thin-disk configuration are discussed. A wavelength tunability of 92 nm is demonstrated, which confirms the potential of $Yb:CaF_2$ for the generation of ultra-short pulses. An output power of 250 W with an optical efficiency of $\eta_{opt} = 47\%$ was measured in CW multimode thin-disk laser operation with a pump spot diameter of 3.6 mm. Using a smaller pump spot diameter of 1 mm the fundamental mode output power was 13 W with an optical efficiency of $\eta_{opt} = 34\%$.

OCIS codes: (140.3615) Lasers, ytterbium; (140.3380) Laser materials.

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1. Introduction

The widespread utilization of ytterbium-doped laser active materials originated from the good availability of diode-pumped laser sources in the spectral range between 900 and 980 nm which precisely match the absorption bands of these materials. The lower quantum defect (ratio of pump to laser wavelength) of these quasi-three-level laser materials allows high optical efficiencies and high output powers due to the reduced thermal load. Noteworthy are also the absence of undesired loss transitions such as up-conversion, excited state-absorption and concentration quenching. Furthermore, the high thermal conductivity in combination with the broad emission bandwidth makes them favorable for high power ultrafast thin-disk oscillators with pulse durations in the picosecond and femtosecond regime.

Ultrafast laser systems have attracted a great interest for many applications ranging from material processing to medical surgery due to their continuously improving reliability and compactness and due to the significant progresses achieved by different research groups [1–3]. Ytterbium-doped materials such as $Yb:CaGdAlO_4$ [4, 5], $Yb:Lu_2O_3$ [6] and $Yb:Sc_2SiO_5$ [7] have recently shown the potential for pulse durations shorter than 300 fs in passively mode-locked thin-disk laser configuration.

The above mentioned properties are also exhibited by the laser active material $Yb:CaF_2$ [8] and are subject of the present paper. Significant efforts were already made in research and development using $Yb:CaF_2$ [9–13], and very recently the shortest pulse duration of 68 fs and an average output power of 2.3 W was demonstrated in a Kerr-lens mode-locked oscillator with a rod crystal geometry [14].

In this paper we present and discuss the challenges on the coating, polishing, mounting and handling of $Yb:CaF_2$ which are a key to achieve efficient high-power laser oscillation in thin-disk configuration. As the aspherical component of the phase front deformation in the disk can be a limiting factor [15] for high-powers and good beam quality in the order of $M^2 < 1.5$, the thermo-optical effects were analyzed experimentally and compared to simulation results. Furthermore we report on the performance of the $Yb:CaF_2$ in CW high-power thin-disk laser operation and the experimental demonstration of the broadband wavelength tunability to confirm its potential for the generation of ultra-short pulses.

2. Properties of $Yb:CaF_2$

The spectroscopic, thermo-mechanical and laser properties of $Yb:CaF_2$ were already discussed by numerous reports [8, 10, 11, 16, 17]. Table 1 summarizes the most relevant material properties of $Yb:CaF_2$ in comparison to those of the well-established Yb:YAG.

At a temperature of 300 K $Yb:CaF_2$ has its main absorption peak at a pump wavelength around 980 nm with a cross section of $\sigma_{abs,pump} = 0.54 \cdot 10^{-20}$ cm^2 [8]. The main emission peaks are reported to be at 1033 nm and 1050 nm with a broad emission bandwidth of 70 nm [18]. The thermal conductivity $\kappa_{undoped}$ of the undoped $Yb:CaF_2$ is comparable to that of the undoped Yb:YAG. But as an advantage over Yb:YAG, $Yb:CaF_2$ has a negative thermal dispersion coefficient dn/dT [8, 19]. With this the contributions from the expansion and from the thermal dispersion to the optical path length in $Yb:CaF_2$ have opposite signs and partly compensate each other which results in a smaller absolute value of the thermo-optical coefficient $\kappa_{th\text{-}opt}$ of $-3{,}7 \cdot 10^{-6}$ K^{-1} than in Yb:YAG and makes the material favorable for high-power fundamental-mode laser operation.

Table 1. Material Properties of $Yb:CaF_2$ Compared to Yb:YAG

	$Yb:CaF_2$	Yb:YAG
λ_{Pump} [nm]	980	940/969
λ_{Laser} [nm]	1033/1050	1030
$\Delta\lambda_{emission}$ [nm]	70	10
$\kappa_{undoped}$ [W/(Km)]	9.7	10.7
dn/dT [10^{-6} 1/K]	−11.3	8.5
Therm. exp. coeff. α_{th} [10^{-6} K^{-1}]	19	6.7
$\kappa_{th\text{-}opt}$ [10^{-6} K^{-1}] = dn/dT + (n-1)·α_{th}	−3.7	13.8
Hardness [Mohs]	4	8.5

However, the low hardness of $Yb:CaF_2$ is a serious challenge for the polishing and mounting process of the thin-disk crystals which at the present stage of the development led to scratches and cracks of the samples as reported in the following section 3.1 and will require further improvement of the techniques for future developments.

3. $Yb:CaF_2$ thin-disk crystals

3.1 The challenges related to polishing, coating and mounting of the crystals

For our thin-disk laser experiments two $Yb:CaF_2$ samples with a nominal doping concentration of 4.5-at. % and a diameter of 10.5 mm were polished down to thicknesses of 200 µm and 250 µm, respectively. Because of the low hardness reported in Table 1 theses thicknesses are higher than the calculated optimum for the mentioned doping concentration [20] in order to reduce the risk of breaking the $Yb:CaF_2$ crystals during polishing. The growing of the used samples was performed without co-doping for charge compensation, as commonly used to reduce cross-relaxation and up-conversion processes. With $Yb:CaF_2$ the resulting benefit of the co-doping remains modest as described in [9] and can even be detrimental for the optical quality and the thermo-optical properties of the crystal. The growing process of $Yb:CaF_2$ without co-doping therefore leads to crystal structure which allows the broadest possible emission bandwidth with minimized deterioration of its optical and thermo-optical properties [9, 21].

Figure 1 shows microscopic images of the surface quality of the polished disks which exhibit large numbers of scratches which will introduce scattering losses and might also affect the adhesion of the coatings. Further improvements will be required, but with the aim of first evaluations and laser tests of $Yb:CaF_2$ in thin-disk configuration the front and the rear side of the crystals were AR and HR coated for the pump and the laser wavelengths, respectively, as required for the experiments. Due to its comparatively large thermal expansion coefficient (Table 1), the $Yb:CaF_2$ thin-disk crystals need careful handling and mounting on the heat sink to avoid damaging.

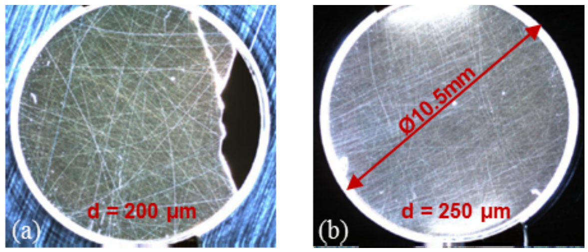

Fig. 1. Microscopic images of two $Yb:CaF_2$ crystals with thicknesses of 200 µm (a) and 250 µm (b).

The HR coated backside of each disk was glued on a water cooled copper heat sink. The radii of curvature measured before and after the mounting process are given in Table 2. The difference of the thicknesses of the AR and the HR coating on the two opposing faces typically leads to a bending of the disks. The asymmetric shape is most probably due to the dissymmetrical stress in the crystal axes in combination with the stress introduced by the coating.

Table 2. Radius of Curvature for the Different Thin-disk Crystals

	After Coating [m]	After Mounting [m]
Disk 1: d = 200µm, 4.5 at.%	$R_x = 0.7$; $R_y = 0.45$	$R_x = 2.2$; $R_y = 2.15$
Disk 2: d = 250µm, 4.5 at.%	$R_x = 1.1$; $R_y = 0.7$	$R_x = 2.8$; $R_y = 2.0$

The interferometric images of the mounted disks after gluing are shown in Fig. 2 – showing the slight aspherical shapes. This deformation does not affect the laser performance in multimode operation and was acceptable for fundamental-mode operation with a small pump spot diameter of 1 mm as reported in the following.

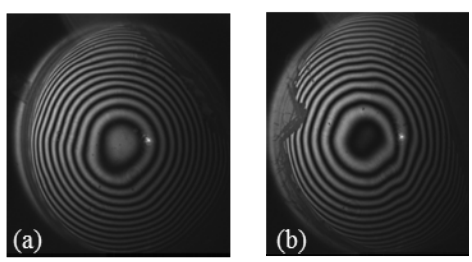

Fig. 2. Interferometric images of the mounted $Yb:CaF_2$ disks with thicknesses of 200 µm (a) and 250 µm (b).

3.2 Characterization of the $Yb:CaF_2$ crystals

In order to monitor the absorption of the pump radiation of the thin-disk crystals the pump power transmitted after 12 of the 24 passes was measured using the standard multipass pumping cavity as commonly provided by the IFSW. The disk was pumped using a fiber-coupled pump diode with a spectral bandwidth of 4 nm centered at a wavelength of 978 nm for an efficient absorption. The pump spot diameter was set to 2.3 mm for these tests.

The internal losses of the resonator were determined to be 0.7% for the 200 µm thick disk and 0.8% for the 250 µm disk by varying the output coupler transmission between 2% and 4% in a simple I-shaped resonator.

The absorbed pump power after 12 passes reaches a maximum of 60% for the 200 µm thick disk and 75% for the disk with a thickness of 250 µm. Hence, with 24 passes the absorbed pump powers are estimated to be almost 84% and 94%, respectively.

The temperatures at the front surface of the disks were recorded using an IR thermo camera. The measurements of the temperature in fluorescence and laser operation are reported in Fig. 3 as a function of the pump power density for the 200 µm and the 250 µm thin disks. As expected, the temperature increases linearly with the pump power density and it is lower in fluorescence operation due to the shorter central wavelength of the spontaneous emission [22]. This behavior is favorable to prevent excessive heating of the crystal and subsequent damaging following an unexpected interruption of laser oscillation, which is usually a problem with Yb:YAG thin-disk lasers. Moreover, the lower quantum defect of Yb:CaF_2 leads to less heat generation in the disk which is favorable for high-power operation. At a pump power density of 7.7 kW/cm^2, the maximum surface temperature in fluorescence operation was 32 °C for the 200 µm thin disk and 35 °C for the crystal with a thickness of 250 µm. In laser operation the temperature was measured to be 87 °C and 94 °C for the two crystals, respectively.

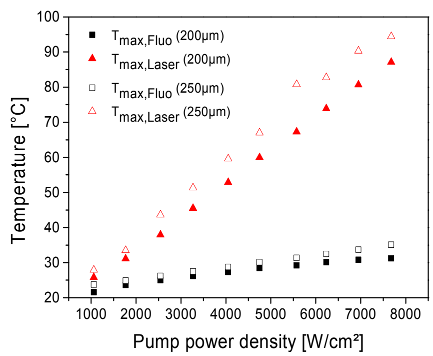

Fig. 3. Measured temperatures at the surface of the disks in fluorescence and laser operation.

In order to further study the temperature distributions in the crystals, FEM (Finite Element Method) calculations using COMSOL Multiphysics were carried out. The temperature distribution of the Yb:CaF_2 disks were calculated assuming a cooling temperature of 15 °C which corresponds to the cooling temperature used in our experiments, a pump spot diameter of 2.3 mm and a heat load resulting from the quantum defect of 5.6% for the different pump power densities of 1.8 kW/cm^2, 4.2 kW/cm^2, 5.7 kW/cm^2 and 7.7 kW/cm^2. The UV-curving glue used to mount the crystals on the heat sink [23] was accounted for by a 2 µm thick layer (corresponding to the target specification).

The calculated temperature distributions are shown in Fig. 4(a) as a function of the radius in the thin disks for a pump power density of 4.2 kW/cm^2. The calculated maximum temperature at the top surface of the crystal is 84.8 °C and 77.5 °C for the 250 µm and the 200 µm thick crystal, respectively. The calculated temperature differences between heat sink and bottom crystal surface across the glue layer amounts to 38 °C and 41 °C, respectively. The temperature difference between the two crystal faces therefore is 36.5 °C and 46.8 °C for the crystals with a thickness of 250 µm and 200 µm, respectively. The lower temperature at the bottom surface of the 250 µm thick disk compared to the 200 µm thick disk can be explained by the radial heat flow through the thicker disk which leads to a better heat removal.

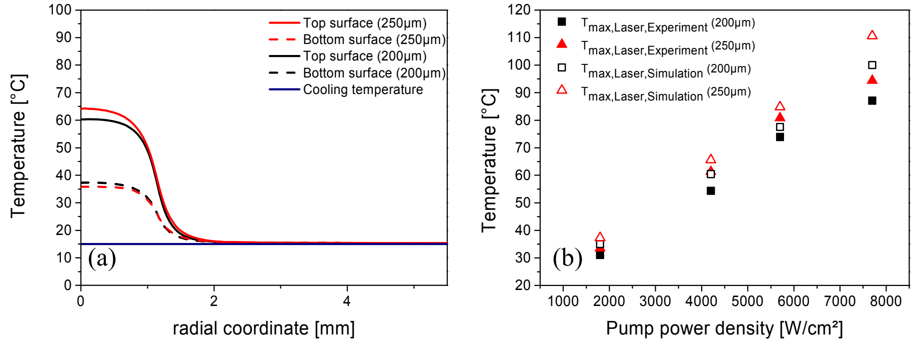

Fig. 4. (a) Simulated temperature at the front and backside of the Yb:CaF_2 crystal at a pumping intensity of 4.2 kW/cm^2 and (b) comparison of the simulated and experimentally measured temperatures at the front surface of the disks.

The simulation and the experimental measurements of the surface temperatures for different pump power densities are in reasonable agreement as can be seen in Fig. 4(b). For a maximum pump power density of 7.7 kW/cm^2 the calculated temperatures are 100 °C for the 200 µm and 110 °C for the 250 µm thin-disk crystal where the experimentally measured temperatures are 87 °C and 94 °C, respectively. These temperatures are the upper limit that can be accepted to avoid damaging of the disks.

4. Analysis and determination of the phase front deformation

The heating of the laser crystal and the corresponding temperature distribution which depends on the pump power density distribution in the thin disk results in two main effects: the geometrical deformation of the disk caused by both the expansion coefficients of the heat sink and the crystal itself and a variation of the refractive index within the disk due to its thermal dispersion (dn/dT). The overall mechanical deformation of the combination of disk and heat sink caused by their different radial expansion is almost spherical at least within the pumped area and can therefore be taken into account by a proper resonator design. The locally varying axial expansion of the disk thickness together with the thermal dispersion, whose combined contributions to the optical path length is characterized by the thermo-optic coefficient $\kappa_{th\text{-}opt}$ (Table 1), closely follows the distribution of the pump light and typically has a non-spherical super-Gaussian shape.

In order to characterize the corresponding non-spherical phase distortions occurring during laser operation of the Yb:CaF_2 thin-disk, detailed interferometric measurements were carried out by means of a home-built UV-interferometer. This high-precision interferometer is essentially based on a Mach-Zehnder-Interferometer with a laser-diode operating at a wavelength of 375 nm which allows measuring the optical path differences even during high-power laser operation. By using a reference beam focused on the center of the disk this set-up allows a precise measurement of the thermally induced path length changes inside and in front of the thin disk with an accuracy down to 5 nm.

For comparison, the phase front deformations were also calculated with the FEM-analysis already mentioned in section 3.2. The pump spot diameter was 3.6 mm for these investigations. For the experiments a symmetrically V-shaped multi-mode resonator with an overall length of 1.2 m was set-up with the disk as the folding mirror, a concave HR with a radius of curvature of 2 m as the end mirror on one side and a plane output coupler with a transmission of 2% on the other side.

The measurement of the optical phase front deformations in the thin-disk laser crystal was limited to a maximum pump power density of 4.2 kW/cm^2 to avoid damaging of the disks. The thin-disk crystal without incident pump power was used as reference. The same investigations were carried out with Yb:YAG which was also glued on a copper heat sink with the same geometry but with a thickness of 180 µm and a doping concentration of 10% as a further comparison.

For a pump power density of 4.2 kW/cm^2 the results are given in Fig. 5 showing a good agreement between experiment and simulations. The depicted distributions of the phase front difference clearly show that the overall deformation of the $Yb:CaF_2$ crystal is much more pronounced due to its larger expansion coefficient as compared to Yb:YAG. From the stepped shape deviation superimposed on the optical phase deformations near the pumped area one can further recognize the opposite sign of $\kappa_{th\text{-}opt}$ in the two crystals. As shown in [15] the step shaped aspherical phase distortion caused in the area of the pump spot can effectively be compensated for means of deformable mirrors to reach kW-class power levels with almost diffraction limited beam quality.

The overall phase distortion in z-direction of the 200 µm (resp. 250 µm) $Yb:CaF_2$ crystal including the global deformation of the mount was measured to be around 450 nm (resp. 1000 nm) whereas it is about 150 nm for the 180 µm Yb:YAG crystal.

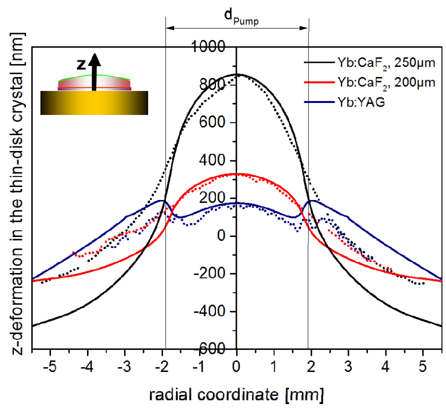

Fig. 5. Comparison of the optical phase distortion caused by a double pass in the $Yb:CaF_2$ and Yb:YAG crystal: experiment (dotted line) and simulation (solid line).

5. Wavelength tunability of $Yb:CaF_2$

The wavelength tuning range of the $Yb:CaF_2$ thin-disk laser was investigated by using different grating waveguide structured (GWS)-mirrors [24, 25] to confirm the potential of $Yb:CaF_2$ for the generation of ultra-short pulses. The schematic setup can be seen in Fig. 6. The wavelengths were monitored with a commercially available USB-spectrometer and the output power in the range of a few Watts was measured in the beams leaking through the GWS-mirror which in this case served as the output coupler with a constant transmission of approximately 0.3 ± 0.2% over the whole wavelength range [26]. The normalized output powers are plotted in Fig. 7 for a relative comparison.

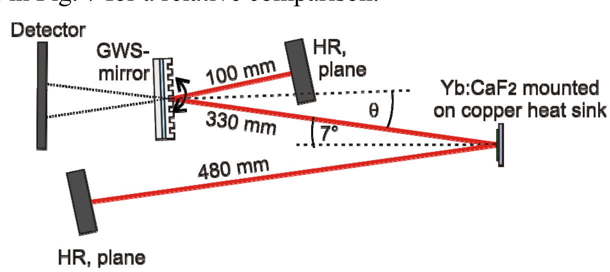

Fig. 6. Schematic setup for measuring the wavelength tunability of $Yb:CaF_2$.

With the available GWS-mirrors, which were not fully optimized for the wavelength of $Yb:CaF_2$, an overall tuning range of 92 nm was measured starting from a wavelength of 993 nm and ending at 1085 nm with a maximum around 1030 nm and a FWHM of 25 mm as shown in Fig. 7. The dips in the spectrum at the shorter wavelengths are not perfectly consistent with the emission spectrum of Yb:CaF_2 [8] and might be due to misalignments of the GWS-mirror. Despite the far from optimized output coupling, the result confirms the broad spectral range provided by Yb:CaF_2 which is promising for the development of ultrafast lasers.

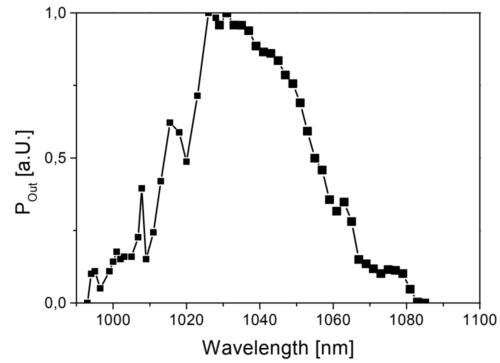

Fig. 7. 92 nm measured wavelength tuning range of Yb:CaF_2 laser crystal.

6. Thin-disk laser performances in CW-multimode operation

The laser performance of Yb:CaF_2 was investigated with a simple I-shaped multimode resonator with the disk as one end mirror and a concave output coupler with a radius of curvature of 500 mm. The transmission of the output coupler was varied between 2% and 4% to find the optimum CW-laser performance. The disk with a thickness of 200 µm was used for these experiments. The resonator length was 200 mm and the pump spot diameter was chosen to be 2.3 mm which led to a measured beam quality factor of approximately $M^2 \approx 20$. For the larger pump spots of 2.9 mm and 3.6 mm the resonator length was increased to 350 mm and 600 mm, respectively, to keep the same beam quality.

With the optimum output coupling of 2% the output powers and the optical efficiencies are shown in Fig. 8 as a function of the launched pump power. A maximum output power of 250 W with an optical efficiency of 47% was reached using the pump spot diameter of 3.6 mm. To the best of our knowledge this is the highest power reported for an Yb:CaF_2 laser to date. Slightly higher optical efficiencies of 50% and 49% at output powers of 145 W and 172 W were reached for the pump spot diameters of 2.3 mm and 2.9 mm, respectively. The slight absolute difference of about 6% may be attributed to local variations of the losses induced by the scratches mentioned in section 3. The central laser wavelength was measured for all experiments to be 1033 nm where the emission cross section has its highest value.

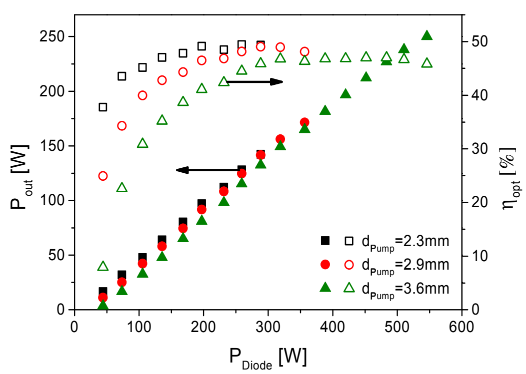

Fig. 8. Power measurement of an I-shaped multimode resonator for different pump spot diameters.

7. Thin-disk laser performance in CW fundamental-mode operation

For the investigations of the fundamental-mode laser performance the pump spot diameter was reduced down to 1 mm because of the observed deformation of the glued thin-disk crystal (Fig. 2), therefore also limiting the available pump power which in this case was provided by a fiber coupled diode with up to 40 W centered at a wavelength of 976 nm with a spectral bandwidth of 10 nm. This large spectral bandwidth is not expected to affect the laser performances of $Yb:CaF_2$ due to its broad absorption bandwidth of 22 nm centered around 980 nm [9].

To ensure a fundamental-mode operation a V-shaped resonator with a total length of 880 nm was used consisting of a concave HR end-mirror with a radius of curvature of 2000 mm and a plane output coupler. The distance between thin disk and the concave HR mirror was 480 mm (leaving 400 mm for the other resonator arm with the output coupler). By varying the transmission of the output coupler between 2% and 5% the optimum output coupling was found to be 3%. The corresponding performance is shown in Fig. 9. A maximum output power of 13 W with an optical efficiency of η_{opt} = 34% was measured. The laser emission wavelength was again around 1033 nm and the beam propagation factor was measured to be $M^2 < 1.1$ over the complete pump power range.

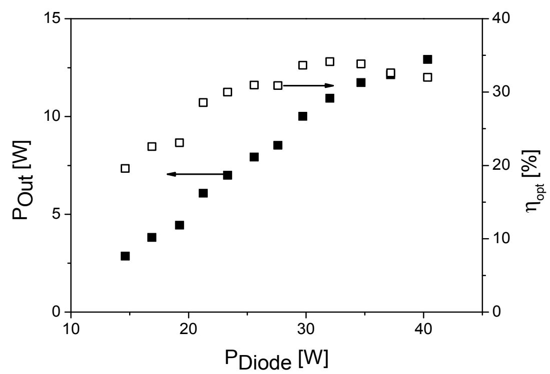

Fig. 9. Power measurement of a V-shaped fundamental mode resonator with 3% of output coupling.

8. Conclusion

In conclusion we have shown the potential of $Yb:CaF_2$ in thin-disk laser configuration for high-power CW operation with a CW multimode output power of 250 W and an optical efficiency of 47%. In fundamental-mode operation 13 W of output power with an optical efficiency of 34% were achieved. The 92 nm broad wavelength tunability range shows the potential for the generation of ultra-short pulses.

Despite the promising results significant improvements with respect to the polishing, mounting and handling of the $Yb:CaF_2$ disk are required to reduce the distortion and the losses and then demonstrate higher power in fundamental mode operation as well as for passively SESAM mode-locked thin-disk laser operation in the femtosecond range.

Acknowledgments

This work was supported by the German Research Foundation (DFG) within the funding programme Open Access Publishing. The author acknowledge Dr. M. Siebold from the Helmholtz-Zentrum in Dresden-Rossendorf for the fruitful discussion concerning $Yb:CaF_2$.