Performance of a quantum defect minimized disk laser based on cryogenically cooled Yb:CaF$_2$

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ABSTRACT

A low quantum defect is the fundamental key to a high efficiency of any laser. To study the anticipated performance boost for a 980 nm-diode pumped cryogenically cooled Yb:CaF$_2$ disk laser we compared its operation at output wavelengths of 991 nm, 996 nm, and 1032 nm. Despite the higher quantum defect a maximum efficiency of 74% (output versus incident power) with an output power of 15.8 W was achieved at the 1032 nm output wavelength. This observation led to a detailed analysis of remaining loss mechanisms we are reporting on in this paper.

1. Introduction

The heat generated in the active medium of an amplifier or oscillator often affects the laser operation. Temperature-dependent emission and absorption cross sections [1] and distorted beam profiles, e.g. due to stress induced birefringence limit the laser performance [2]. Furthermore, the quantum defect fundamentally limits the minimally achievable heat load in the material during the laser process. The quantum defect is the fraction of the pump photon’s energy which is not transferred to the laser photon due to the latter’s longer wavelength. It also limits the maximum efficiency of the laser process. Yb$^{3+}$ is an interesting candidate for a laser ion with minimal quantum defect due to its simple electronic structure. There are only two energy levels, each broadened by the Stark-splitting of the host material. In the most common case of Yttrium-Aluminum-Garnet (YAG) as the host material, its thermal conductivity at room temperature and 3 mol% doping is 4 W/(m K) [6] i.e. about a factor of two smaller than that of YAG, but its spectral properties are much better suited for operation with a low quantum defect. Fig. 1 shows the effective cross sections $\sigma_{\text{eff}}(\lambda)$ of Yb:CaF$_2$ at 80 K temperature for different inversion levels. Here, $\sigma_{\text{ems/abs}}$ are the emission and absorption cross sections respectively, and $I$ is the inversion, i.e. the density of Yb-ions in the upper Stark manifold divided by the doping density.

As it can be seen in Fig. 1, the zero-phonon line of Yb:CaF$_2$ is at 980 nm with a FWHM width of 1.8 nm [7] which enables pumping with a laser diode stabilized by a volume-bragg grating (VBG). Additionally, suitable emission lines of Yb:CaF$_2$ (991 nm, 996 nm and 1030 nm) are closer to the pump wavelength, hence reducing the quantum defect. While the applications for wavelengths in the 996 nm regime are the same as for 1064 nm lasers, the detection with silicon photodiodes is much easier [8]. Nevertheless, cryocooling of the laser material is necessary to suppress the reabsorption at such wavelengths by reducing the thermal population of the lower laser level. A similar approach to operate a Yb:CaF$_2$ laser at low quantum defects was already described by S. Ricaud et al. [9]. An efficiency of 35% output power versus absorbed pump power was achieved with a bulk-laser setup. In [10] N. Ter-Gabrielyan et al. report on a similarly low
quantum defect in Er:Sc$_2$O$_3$, but the efficiency was limited to about 44% output power versus absorbed power.

One of the main problems with such a small quantum defect is the separation of the pump and the laser beam because dichroic mirrors require a larger wavelength separation. This can be solved by using a disk laser setup in which pump and laser beams are separated by an angle. Furthermore, due to the quasi-three-level behavior of laser ions with small quantum defects, the disk laser scheme is also better suited for these applications. Compared to a bulk laser setup, the higher number of pump passes increases the effective pump intensity and the smaller active volume increases the inversion (at constant absorption).

K. S. Wentsch et al. [11] reported on a Yb:CaF$_2$ thin-disk laser with an output power up to 250 W, 47% optical efficiency, and a 92 nm wide tuning range. However, no significant output power was achieved at 996 nm. As they describe, the preparation of disks thinner than 250 µm is very challenging because CaF$_2$ is more brittle than YAG.

2. Experimental setup

Here, we report on the realization of a cryogenically cooled, Yb:CaF$_2$-based disk laser which could be operated at different laser wavelengths. With the setup depicted in Fig. 2 we were able to reduce the laser’s quantum defect down to 1.1% only. To allow for cryogenic cooling of the Yb:CaF$_2$ disk, the whole optical system was placed inside a vacuum chamber to prevent intra-cavity losses from windows. Using a vacuum vessel with a diameter of 16 cm, six double passes of the pump radiation could be realized in our setup. To prevent fiber-facet damage, the pump passes from the last turning mirror back to the pump fiber could not be used. Hence, only three pump double passes were used with much smaller pump absorption efficiency than possible with this design. In the future this could be overcome by a modified pump head or a fiber facet with protection against back reflections.

Disks with a thickness of 0.5 mm were used, more than what is typical for thin-disk lasers. As a consequence, thermal lensing could not be suppressed as efficiently as for thinner disks. Nevertheless, the effect of thermal lensing was calculated not to be relevant due to the low thermo-optical coefficient of $-2.45 \cdot 10^{-6}/\text{K}$ [12]. The applied thickness is a compromise between high absorption at low doping concentration (3 mol%) for good thermal conductivity and a high spatial overlap of the pump beam and the resonator mode. Because of the mainly axial heat flow the usual power scalability of disk lasers [13] still applies. The disk’s backside was coated HR > 99.8% and the front side was coated AR < 0.2%, both for 980–1030 nm.

The laser disk and the copper heatsink were thermally contacted using an eutectic alloy consisting of gallium, indium and tin. Since this metal is liquid at room temperature the disk could be fixed to the heatsink with a drop of it in between. At -19°C the alloy solidifies but stays soft like indium in the whole temperature range of the experiment. Hence, the stress originating from the thermal expansion difference of copper and CaF$_2$ could be minimized.

Cooling was provided by a closed loop cryorefrigerator (CP800, Cryomech Inc.). The cooling head was connected to the heatsink via a copper rod to decouple it from the mechanical vibrations. The heatsink was then connected to the pump head with fibreglass bolts reducing the thermal contact here. The heat sink could be cooled to $T < 30$ K in our vacuum chamber without cooling the other parts of the setup. The temperature inside the heatsink was measured with a silicon diode sensor (DT670). Since the copper wire is the bottleneck for the heat flow, the heatsink temperature is a measure for the optically generated heat during steady-state cooling. Using the power-temperature curve from a reference measurement with an ohmic resistor, the heat generation of the laser material could be measured under operation. Under a heat load of 6 W the heatsink temperature increased to 35 K.

Pressures of $2 \cdot 10^{-6}$ mbar were reached using a turbomolecular pump. Furthermore, the pressure was reduced below $5 \cdot 10^{-6}$ mbar at $T=30$ K. This indicates that a part of the remaining gas in the chamber was condensing on the heat sink, potentially decreasing the laser performance.

As the pump source a VBG stabilized laser diode (LuOcean, Lumics GmbH) was used. Its output was coupled into a multimode fiber with a core diameter of 105 µm. Including the coupling losses it delivered up to 21.3 W of radiation to the laser disk. The output spectrum of the diode peaked at 980.4 nm with a FWHM of 0.4 nm. At this wavelength and at 80 K the absorption of Yb:CaF$_2$ is at a maximum.

The laser cavity only comprised the laser disk and the output coupler (OC). Since the gain in the disk is small and additional optical elements would lead to losses of the same order, all wavelength tuning had to be accomplished using the OC. For this purpose, two approaches were tested: First, we used a spectrally filtering OC with $T$–1% at 996 nm and $T > 50\%$ at 1030 nm i.e. laser operation was suppressed at the latter wavelength. Second, we used different spectrally flat OC’s with a transmission of up to 5%. Because of the reabsorption on the laser wavelength in quasi-3-level media the wavelength with the highest gain depends on the inversion of the laser material (see Fig. 1). This means that by increasing the inversion by increasing the output transmission of the oscillator, one can also decrease the output wavelength.

3. Numerical calculations

We carried out numerical simulations using the COMSOL Multiphysics heat transfer module to calculate the temperature distribution for a given 3D-heat source and a fixed temperature of the cooling finger. The recorded pump-spot profile was used as the heat source and the integral heat generation was set to the measured value (see below). This simulation has shown that the average temperature of the emitting area is about 50 K higher than the heatsink-temperature.

Additionally we performed numerical calculations based on the data from [7] to compute the operation wavelength for the different OC’s at temperatures between 300 K and 80 K. Although the
cryorefrigerator could be used down to T < 30 K, adding the mentioned 50 K from the heat source in the active material results in an average temperature of 80 K at full pump power. For each temperature data set and each OC we calculated the average inversion necessary to fulfill the threshold condition

$$I < \frac{G(\lambda)}{V R(\lambda) \exp(\sigma_{\text{eff}}(\lambda) 2nL)}$$

and the wavelengths of the highest gain $G$. Here $R$ is the reflectivity of the OC, $V$ includes all other losses in the cavity, $n$ is the doping density and $L$ is the length of the gain medium.

The open squares in Fig. 3 show the results of the numerical calculation. The 5% OC is expected to emit at wavelengths of 991 nm at 80 K. The spectrally filtering OC suppresses the operation at 1032 nm. At temperatures below 100 K we expect laser operation at 996 nm.

### 4. Results and discussion

The most efficient operation was achieved using an OC with 1% transmission at 1032 nm. As Fig. 4 shows, an output power of 15.8 W was measured outside the vacuum chamber with a heatsink temperature of 30 K. This corresponds to an optical efficiency of 74% incident pump power to output power including all optics and windows between the OC and the detector. Before the thermal rollover an efficiency of 78% has been achieved. This is to the best of our knowledge the highest efficiency with regard to incident pump power ever reported for solid state Yb-lasers. D. J. Ripin et al. [14] reported 76% optical efficiency for a cryogenic Yb:YAG laser with 165 W output power and close to diffraction limited beam quality. More recent experiments with a similar setup by T. Y. Fan et al. [15] resulted in 71% efficiency at 455 W output power. R. Peters et al. [16] achieved 72% optical efficiency with an Yb:Lu$_2$O$_3$ disk laser at room temperature emitting more than 32 W, and an $M^2$-factor between 10 and 20. Weichelt et al. [17] report on a room temperature Yb:YAG disk laser with 72% optical efficiency and an $M^2$ of 15. While D. Brown et al. have reported on 84% optical-to-optical efficiency in a cryogenic Yb:YAG laser [18], this value has been calculated versus absorbed power, which was about 63% of the pump power. We consider the incident pump power to be more relevant since the pump absorption is part of the physical problem. Especially in 3-level media it cannot be increased without significantly changing the emission characteristics, the thermal behavior, or the pump geometry which in most cases changes the overlap efficiency.

The reason for the thermal rollover in Fig. 4 is not thermal lensing, but rather the decreasing absorption and emission cross sections when the laser material’s temperature increases.

Now we will estimate the distribution of the pump energy into the different loss channels. The aforementioned calculation yields an inversion of $I=0.033$ when operating at 80 K. Due to the spatial limitation of the number of pump passes to 6 passes rather than 12, 7.5% of the pump power was transmitted and not absorbed. The transmission of the laser disk’s rear surface was measured to be 0.04% for 1032 nm. Together with the 1.2% transmission of the OC (measured), this leads to 0.51 W laser light (2.4% of the pump power) heating up the heat sink. The fluorescence losses due to the lasing threshold were 0.18 W (0.8% of the pump power). Another 2% of the pump power was lost at the optics in the pump head and the output coupling window of the vacuum chamber. The quantum defect is 5%, corresponding to 0.86 W heat generation (4% of the pump power). The effective heat source of the 15.8 W laser operation was measured to be 2.27 W. This is equivalent to only 15% of the laser output power. This low value leads to reduced thermal distortions of the beam profile. In [19] D. E. Miller et al. report on a cryogenic Yb:YFL laser with similarly low heating per Watt of output power and about 70% efficiency versus absorbed power.

Since the quantum defect and the transmission of the disk’s rear surface only account for a heating of 1.37 W, there is another effect causing a parasitic heating of 0.9 W (4% of the pump power). The quantum efficiency of Yb:CaF$_2$ is reported to be close to 100% by multiple sources ([20] 98 ± 3% and [21] 99.3%), so an impurity or disturbance in the laser material is likely responsible for this.

Due to the operation within a vacuum chamber the unabsorbed pump power could not be measured directly, but we assume by the temperature of the beam dump (i.e. the wall of the vacuum chamber) that more power than calculated was absorbed. The relative error of the peak cross sections that our calculation of the absorbed power was based on is rather high due to the measurement setup described in [7]. The difference between the peak cross section values published in [7] and [12] shows that the peak cross sections of Yb$^{3+}$ are a topic of debate and that calculations based on these values can only be considered estimates.

Our Yb:CaF$_2$ was supplied by Korth Kristalle GmbH and shows a slight violet fluorescence under 980 nm pumping. We suspect color centers similar to the ones mentioned in [22] to be responsible for the parasitic heating, either by direct pump absorption or by energy transfer from the Yb$^{3+}$ ions. Color centers are temporarily created by the intense pump radiation, but their lifetime increases at cryogenic temperatures. That is why this heating mechanism could not be measured in [20] although they used the same production charge of Yb:CaF$_2$ as we did.

Table 1 shows an overview over the losses for each realized cavity. All losses are given in values relative to the incident pump power. The category “remaining” is 100% minus the sum of all other losses and
minus the optical efficiency. Since the quantum efficiency of the Yb:ions alone is close to one, there are only two types of losses left, which have so far not been included: The energy transfer to color centers or impurities and the overlap efficiency between the profile and the cavity mode. The parasitic heating value is the measured heat source that is not explained by the disk’s rear surface and the quantum defect. Due to the low threshold the heating by the fluorescence to have a super-Gaussian intensity profile of 2.45th order and a 1/e²-diameter of 2ω0 = 620 µm rather than a top-hat profile. This is because the disk is comparably thick and the pump spot shape changes along the optical axis in the disk. For this experiment the OC curvature was chosen such that the fundamental mode had a diameter of 2ω0=300 µm. The \( M^2 \)-factor of the output beam was measured with camera pictures of the beam profile around a focus. The first- and second-order moments of the beam were calculated and the resulting diameter \( d \) was fit according to ISO 11146 [23]. The resulting \( M^2 \)-factor of the 1032 nm beam at full power was 2.4, the measurement curve and beam profiles are shown in Fig. 5.

The emission spectrum consisted of seven narrow (FWHM < 0.25 nm) peaks between 1029 and 1034 nm. The distance of 0.7 nm between the peaks agrees with the etalon properties of the laser disk. In the case of 996 and 991 nm emission, the emission spectrum was much narrower and only had 3–4 peaks.

Laser operation at 991 nm with an ultra-low quantum defect of 1.1% was achieved with a 5% transmission OC. The experiment was also carried out with a multimode cavity (2ω0 = 300 µm). The output wavelength versus heatsink temperature is shown in Fig. 3 and the power/efficiency in Fig. 4. If we keep in mind that the average temperature in the laser material is about 50 K above the temperature of the heatsink at full pump power, the experimental data fit the calculation quite well. The \( M^2 \)-value of the beam emitted from this cavity was about 3, independent on the lasing wavelength of 991 nm or 1032 nm. The beam profiles were in all cases similar to the ones shown in Fig. 5.

Interestingly, laser operation at a wavelength of 991 nm was not stable. 20–40 min after start-up at 30 K the laser showed a tendency to switch to 1032 nm operation and stayed there for unknown reasons. This may be caused by the mentioned color centers or by the vacuum conditions, since some of the rest gas in the chamber condenses on the heat sink. Rayleigh-scattering off these particles would be strongly favored for shorter wavelengths, just as the absorption in the color centers. In Fig. 4 the wavelength changes slowly around 12.5 W pump source, since the pump heats up the material and then also prefers the higher wavelengths, but the effect was mostly advancing by the operation time at 30 K. Note that due to the already low pump absorption, it would be useless for wavelength tuning to further increase the OC transmission.

The parasitic heating with the 5% OC was 12.1% of the pump power. That is much more than in the case of the 1% OC, probably because the low pump absorption of the Yb-ions leads to a higher absorption of the color centers (since the unabsorbed radiation passes the disk again). Again, although we were not able to measure it directly, we suspect the unabsorbed part of the pump was actually much smaller than 23.5%.

Stable laser operation at 996 nm was achieved with the spectrally filtering OC. 13 W of output power and an optical efficiency of 61% were recorded with a quantum defect as low as 1.6%. The OC transmission at 996 nm was 0.91%. As seen in Fig. 3 the output wavelength matches the calculation quite well when keeping in mind that the heatsink temperature at full pump power is about 50 K lower than the temperature of the emitting area. The predicted emission at 1064 nm at room temperature could not be observed because the disk’s coating was optimized for 990–1030 nm, which was not included in the wavelength calculation.

There are two reasons that the efficiency of this operation mode was smaller than for operation at 1032 nm. First: Due to the higher threshold inversion the absorbed pump power was lower. Second: The spatial overlap seems to be worse. Since only one spectral OC was available for the measurements presented here we chose an OC radius that the fundamental mode diameter was 2ω0 = 510 µm. This led to the excellent beam quality with M²=1.2 but as shown in Table 1 the “remaining” value increases. We attribute this to a decreased spatial overlap between pump and cavity mode.

At a heatsink temperature of 80 K, which is easier to maintain, an optical efficiency of 70% was achieved under full pumping at 1032 nm with the 1% OC and 55% optical efficiency was achieved with the spectral OC at 996 nm output.

5. Conclusion

We have demonstrated operation of a cryogenically cooled Yb:CaF₂ disk laser with a record high optical efficiency of 78% versus incident pump power. The heat generation at the heatsink was as low as 15% of the output power. The different loss mechanisms were discussed. From the comparison with results from other groups [9,10,16] we conclude that a disk laser scheme is optimally suited for efficient operation at a small quantum defect. An optical efficiency of 61% was achieved at a quantum defect of only 1.6% with output powers of up to 13 W and a near diffraction limited beam quality of M²=1.2. It turned out that the heat generated by small impurities or color centers exceeds the heat reduction from the decreased quantum defect. We therefore conclude...
that when aiming at a decrease in heat generation by a reduction in quantum defect, the purity of the laser material and the quantum efficiency under pumping conditions become more important.

Our approach to reach high efficiency operation and low heat generation can obviously be improved by increasing the number of pump passes and by using purer host materials.

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References


