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# Cr:ZnSe Thin Disk cw Laser

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**Abstract:** A Thulium fiber laser pumped or InP diode laser stack pumped Cr:ZnSe thin disk cw multimode laser at 2.4  $\mu\text{m}$  with an output power of 5 and 4 W, respectively, and with optical-to-optical efficiencies of 10% will be presented. An experimentally verified and numerically simulated thermal lensing induced and cyclic instability in the laser system will be shown. As a consequence, in order to prevent the lasing conditions in the resonator to be unstable, power scaling of a Cr:ZnSe thin disk laser is possible by enlarging the pump spot and reducing thereby the thermal lensing condition. Therefore, the instability is not initiated. As a conclusion, the investigated instability will show up in any laser active material which has a strong absorption of the pump beam, for instance in transition metal ion laser material systems in connection with any laser concept, like for instance in thin disk, bulk or slab designs.

**Keywords:** thin disk laser, Cr:ZnSe, thermal lensing instability, power scaling

## 1. Introduction

Chromium-doped II-VI semiconductor compound laser crystals emit in the 2  $\mu\text{m}$  ‘eye-safe’ wavelength region and are therefore attractive for use in remote sensing, laser material processing, laser surgery as well as military applications. Compared to the narrow tunable rare-earth ion (Er, Ho, Tm etc.) doped crystals, the transition metal ion (Cr, Co, Ni, or Fe) doped crystals are broadly tunable in the mid-IR range. The material properties of Cr<sup>2+</sup>:ZnSe shows some remarkable characteristics, for instance, tunability between 2 and 3  $\mu\text{m}$ , a high emission cross-section of  $\sim 1 \times 10^{-18} \text{ cm}^2$ , a negligibly low excited state absorption (ESA) and a good chemical and mechanical stability as well as good thermal conductivity. Disadvantages of the Cr:ZnSe material are the relatively high thermal lensing parameter  $dn/dt$  of  $\sim 70 \times 10^{-6} \text{ K}^{-1}$  or the temperature dependent upper lifetime reduction between 10 and 1  $\mu\text{s}$ . The short upper lifetime of Cr:ZnSe compared to the ms-region of rare-earth ion materials leaves Cr:ZnSe hardly any energy storage capabilities but shows switching capabilities for self-oscillation modes in the 100 kHz and 100 ns range. Due to the broad absorption band between 1.5 and 2.1  $\mu\text{m}$  of Cr:ZnSe, pumping from a wide variety of laser sources like Er or Tm active ions are possible [1, 2]. Thermal effects in Cr:ZnSe thin disk lasers have been investigated in the past by Schepler et al. [3] and it was concluded that thermal lensing and disk overheating were crucial issues in the relatively low output power of 1.4 W achieved. In this report a Cr:ZnSe thin disk cw laser will be pumped either by a Tm fiber laser at 1.9  $\mu\text{m}$  or by a narrowband (2 nm, FWHM) InP diode laser stack at 1.9  $\mu\text{m}$ . For the Cr:ZnSe thin disk cw laser a multi-pass pumping scheme will be used with 24 pump passes [4, 5]. In the past, there has only been a minor progress in room temperature power scaling a Cr:ZnSe thin disk laser. Nonetheless, using the concept of thin disk multi-pass pumping with its inherent good thermal management scheme should open the opportunity of scaling Cr:ZnSe thin disk laser systems into power range comparable to recently developed Cr:ZnSe bulk laser systems of the order of 10 W [6, 7].

## 2. Experimental setup and results of the Cr:ZnSe thin disk cw laser system

The thin disk single-crystal material has been grown by physical vapour transport. The Cr<sup>2+</sup>-ions have been introduced into the ZnSe infrared material by thermal diffusion below the ZnSe melting point. The front side of the disk is anti-reflection coated and the back side is high-reflection coated for the pump and laser wavelengths. The diameter of the disk is 4 mm and the disk has a thickness of 250  $\mu\text{m}$ . The back side of the disk is cooled by heat transfer to a copper finger which is cooled by a water flow at 10°C. The thin disk is pressed on a cooling finger using indium layer. Either a single mode fiber laser pump beam (IPG Photonics, 50 W) or an InP diode laser stack pump beam (QPC Laser, 40 W) is transferred through a multimode fiber and collimated into the disk laser module (Dausinger + Giesen GmbH). The parabolic mirror of the disk laser module with a focal length of 3.25 cm focuses the pump beam in 24 pump passes onto the Cr:ZnSe thin disk with a pump spot diameter in the order of 0.7 mm.

Due to the high absorption of the pump wavelength of approximately  $5\text{ }\mu\text{m}^{-1}$ , almost all of the pump power is absorbed in 24 pump passes. The layout of the thin disk laser is shown schematically in figure 1. The resonator type is a hemispherical setup. The output mirror has a radius of curvature of 10 cm and the resonator length is approximately 10 cm. The output coupling of the output mirror is 2%.

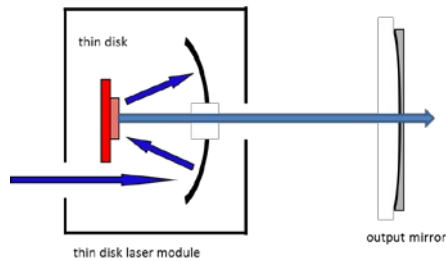


Fig. 1. Schematic layout of the Cr:ZnSe thin disk cw laser system.

In figure 2 (left) an infrared picture done with a pyro-electric camera (Pyrocam III) of the pumped disk is shown with a pump spot of approximately 0.7 mm. For a pump power of 50 W, the pump power density reaches  $10\text{ kW/cm}^2$ . Additionally, the illuminated rim of the disk, originating from the transverse amplified spontaneous emission (ASE) leaving the disk in radial directions through the bulges of the lead layer, can be seen. In the right picture of figure 2 an interferometric measurement of the cold disk is shown. Due to the cold pressing technique of the disk onto the copper cooling finger with an indium layer, the disk shows a negative radius of curvature in the order of 1.5 m and has therefore defocussing properties.



Fig. 2. Infrared picture of the pumped disk (left) and interferometry picture of the cold disk (right).

For wavelength tuning of the Cr:ZnSe thin disk laser a birefringent filter consisting of two Brewster angle tilted quartz plates with thicknesses of 2 and 8 mm is installed into a linear resonator consisting of the disk, a focussing lens and a flat output mirror. The measured spectra with the tuned lines are shown in figure 3.

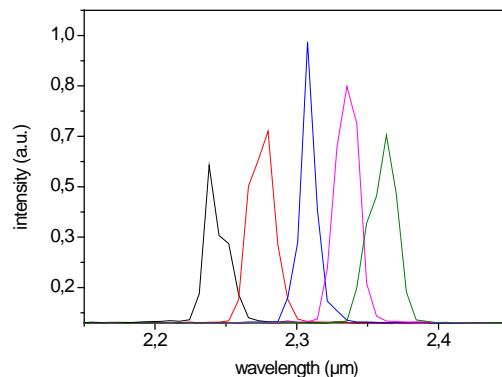


Fig. 3. Tuning curve of the Cr:ZnSe thin disk cw laser done with a Lyot filter.

The output power reached the 100 mW power level. The single lines show linewidths between 1 and 2 nm (Jobin Yvon, resolution < 1 nm). In figure 3 the tuning between 2.23 and 2.37  $\mu\text{m}$  is shown which has been measured with a low resolution spectrometer (OceanOptics, 17 nm resolution). Figure 4 shows measurements of the absorption and the emission cross-sections and the calculated gain, compared to that for the case of a single-pass longitudinal pumping [8]. While emission cross-section measurement is free of re-absorption, the actual amount of re-absorption depends on pump power density along the beam path. The multiple-pass thin disk pumping scheme provides very uniform saturation of absorption. From the gain cross-section curve of figure 4 it can be recognized that between 2 and 2.4  $\mu\text{m}$  there is a broad shoulder which is responsible for the relatively constant laser output power down to 2  $\mu\text{m}$ .

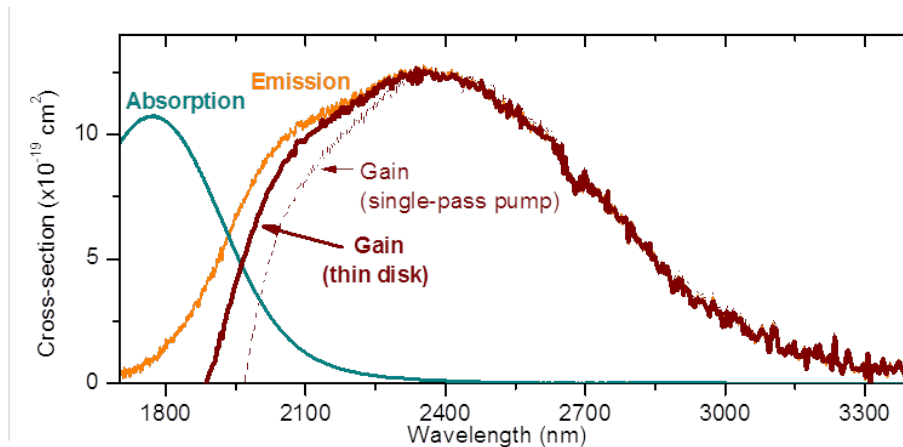


Fig. 4. Absorption and emission cross-section measurement of Cr:ZnSe and the calculated gain for the case of single-pass longitudinal pumping (corresponds to Fig. 10 in [8]) and the multi-pass thin disk configuration.

The output power of the Cr:ZnSe thin disk cw laser, pumped with a Tm fiber laser (IPG Photonics) launched into a 1000  $\mu\text{m}$  transfer fiber at 1.908  $\mu\text{m}$  or pumped with a fiber coupled narrowband (2 nm, FWHM) InP diode laser stack around 1.908  $\mu\text{m}$  (QPC Lasers) with a 600  $\mu\text{m}$  fiber coupling to the thin disk module, is shown in figure 5. For the fiber laser pumped case an output power of 5 W has been realized at an optical-to-optical efficiency of 11% and with a wall-plug efficiency in the order of 1%. For the InP diode laser stack pumped case an output power of 4 W has been achieved at an optical-to-optical efficiency of 10%.

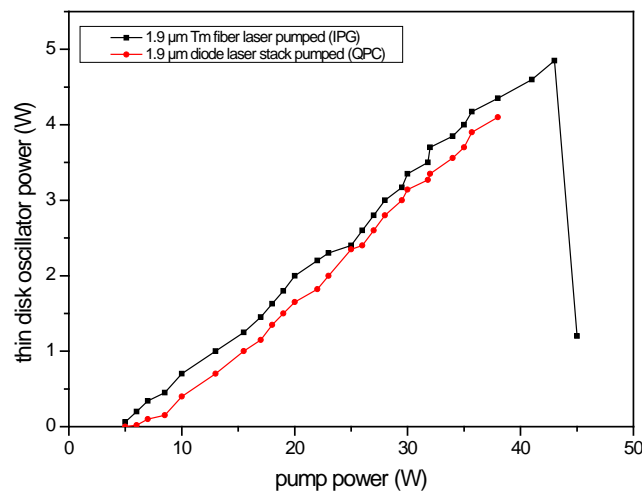


Fig. 5. Output power of the Cr:ZnSe thin disk cw laser versus pump power for fiber laser and diode stack pumped system.

Due to the fact that the Tm fiber laser pump system starts with diodes at 930 nm to pump the Yb-, Er- and finally the Tm levels, the wall-plug efficiency is here lower compared to the direct diode stack pumping. The highest output power realized so far is 6 W using a 1500  $\mu\text{m}$  transfer fiber between the single mode fiber of the Tm fiber laser and the thin disk module which gives an efficiency of 8% (Fig. 6).

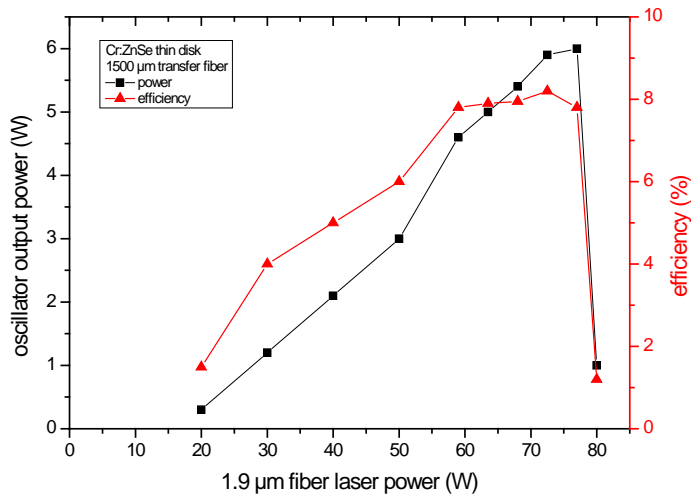


Fig. 6. Output power of the Cr:ZnSe thin disk cw laser versus 1.908  $\mu\text{m}$  fiber pump power.

In figure 6 the oscillator output power shows a linear power scaling up to 6 W before it turns into saturation. Above 6 W a sudden breakdown of the lasing action occurred which can be withdrawn by lowering the pump power by a few per cent. After this procedure, the original output power of 6 W will be reached again. This phenomenon can be described as a cyclic instability and it will appear in any transition metal ion laser system with strong pump power absorption. Furthermore, the instability is not restricted to a thin disk design but has to be considered in a bulk or slab laser design as well. In figure 7 the broadband emission spectrum around 2.4  $\mu\text{m}$  with a linewidth of 50 nm (FWHM) is shown which makes the Cr:ZnSe thin disk laser suitable for ps and fs pulse generation.

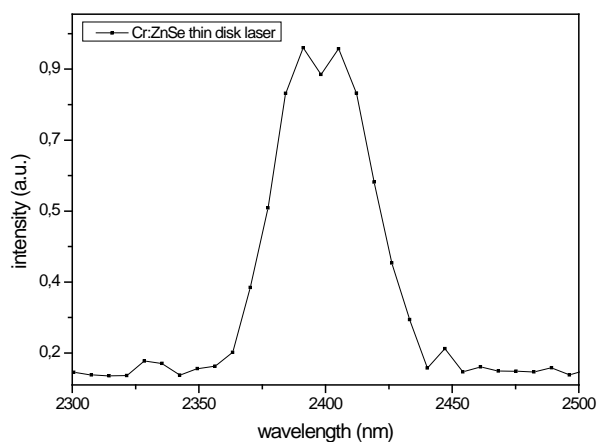


Fig. 7. Broadband spectral line of the Cr:ZnSe thin disk laser output.

In figure 8 the cw Cr:ZnSe thin laser output of a hemispherical resonator with an output coupling of 2% and a radius of curvature of 10 cm of the output mirror is depicted versus the resonator length.

As can be seen, a strong variation of the output power results from a small variation in the resonator length due to the hemispherical resonator type.

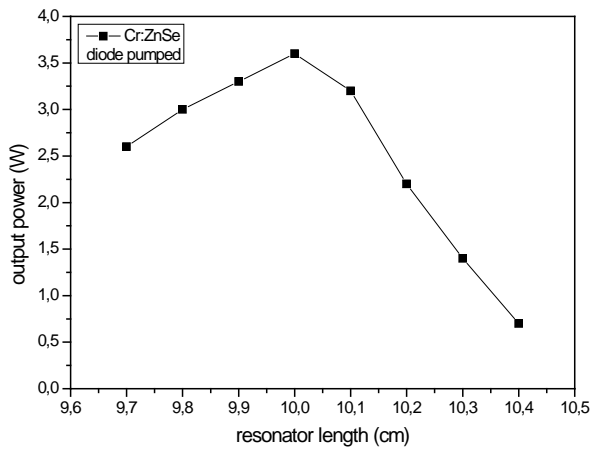


Fig. 8. Multimode output power versus resonator length of a hemispherical resonator.

### 3. Theoretical investigation of the cyclic instability in a Cr:ZnSe thin disk cw laser

The investigation of the cyclic instability in a Cr:ZnSe thin disk cw laser should lead to an improvement of the laser performance and should open up the possibility of power scaling these lasers. The question arises about what causes this cyclic instability to occur. As mentioned in the introductory part of this report, Cr:ZnSe shows a temperature dependent upper lifetime, decreasing almost linearly for temperatures above 350°K [see Fig. 22 in 1]. Therefore, this linear decrease of the upper Cr<sup>2+</sup>-lifetime cannot be the reason for this sudden initiated instability with a dramatic loss of output power. In the following, the influence of the thermal lensing will be investigated. The procedure to describe the influence of the thermal lensing on the output power will be a numerical 3-dimensional approach. The thermal lens will be treated as a three dimensional object. Starting with the three dimensional temperature distribution inside the thin disk, the three dimensional local optical phase distortion (OPD) can be calculated with the known material properties of ZnSe [9, 10]. The local optical phase distortion acts on the optical local laser field as a disturbance. Therefore, a Fast Fourier Transform (FFT) technique will be used to calculate the amplified optical laser field in the resonator, starting from the spontaneous emission level. The calculated three dimensional result of the temperature distribution inside the 250 μm thin disk with a disk diameter of 4 mm is shown in figure 9. It is assumed that 1/3 of the pump power goes into heat. As can be seen, the front side of the disk shows the high temperature values whereas the back side is cooled.

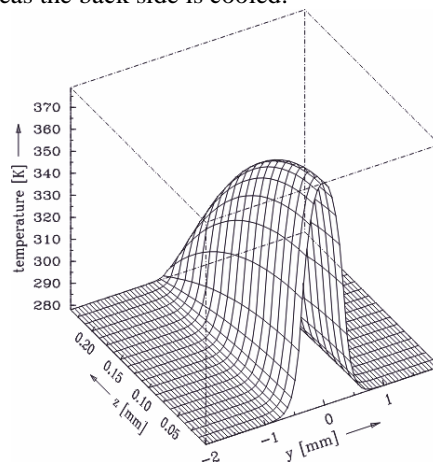


Fig. 9. Temperature distribution inside the Cr:ZnSe disk.

With the temperature distribution and the Cr:ZnSe material properties, the optical phase distortion change can be calculated with:

$$dOPD(x, y, z) = \frac{dn}{dt} \cdot \Delta T(x, y, z) \cdot dz + \alpha \cdot l_d \cdot \Delta T(x, y, z) \cdot dz$$

The first term is caused by the thermal dispersion and the second term describes the thermally induced axial expansion of the disk with a thickness  $l_d$ . In figure 10 (left) the optical phase distortion is depicted and in figure 10 (right) the axial expansion part of the optical phase distortion is shown in units of the laser wavelength. The thermal expansion part of the optical phase distortion makes up for 17% and has therefore a minor impact.

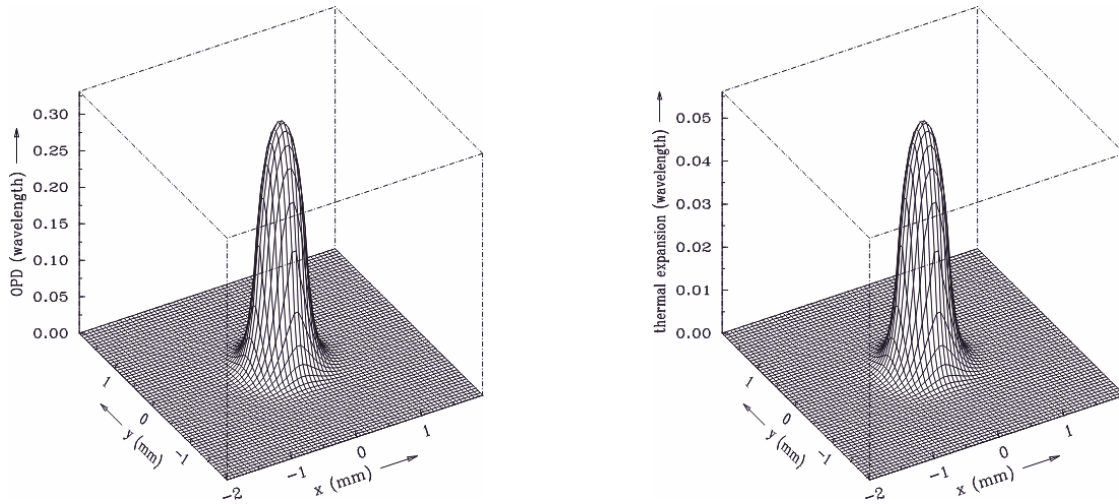


Fig. 10. Optical phase distortion caused by thermal lensing (left) and thermal expansion part (right).

The oscillator output power of the laser field, starting from the spontaneous emission level, can be numerically calculated by solving the differential wave equation in three dimensions under the simplification of the slowly varying amplitude approximation. The 10 cm long linear hemispherical resonator consists of the thin disk with the cooled high reflection side and an output coupler with a radius of curvature of 10 cm and an output coupling of 2%. For the amplification, a small signal gain of  $0.03 \text{ cm}^{-1}$  and for the saturation intensity  $20 \text{ kW/cm}^2$  was assumed. In figure 11 the relative oscillator output power versus the power transferred into heat is depicted.

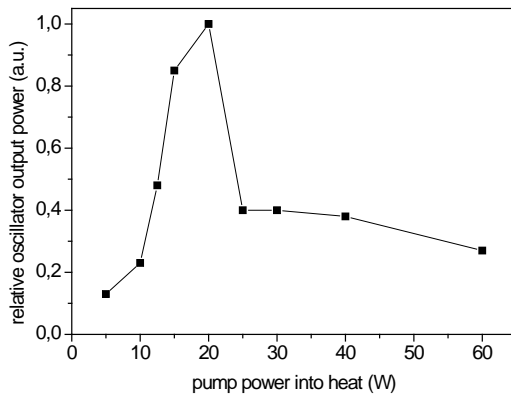


Fig. 11. Relative oscillator output power versus pump power transferred into heat.

After increasing the part of the pump power from a low power level up to 20 W, a sudden drop of the output power can be noticed, consistent with the experimental measurement. The increased thermal lens with an estimated focal length in the order of 10 cm leads to unstable resonator conditions. This instability can therefore be identified being caused by the thermal lensing effect of the pumped thin disk equivalent to thermal self-focusing. The occurrence of this instability will further be recognized at any laser material system which shows a strong absorption of the pump beam, either in a thin disk, bulk or slab design.

#### 4. Summary

In conclusion, Chromium doped ZnSe or ZnS thin disk laser concepts are able to reach the power level of Cr:ZnSe bulk laser systems and show the potential to be scaled even beyond these power levels. A Thulium fiber laser pumped or InP diode laser stack pumped Cr:ZnSe thin disk cw multimode laser at 2.4  $\mu\text{m}$  with an output power of 5 and 4 W, respectively, and with optical-to-optical efficiencies of 10% has been realized. Additionally, a maximum of cw laser output power of 6 W for a Cr:ZnSe thin disk laser with a larger pump spot has been realized at a lower efficiency of 8%. Concerning electrical power consumption, it was shown that pumping with a diode laser stack has a higher wall-plug efficiency compared to the fiber laser pumped case. Chromium doping of the used ZnSe material was done by a thermal diffusion technique. For future Cr:ZnSe thin disk laser scaling experiments it might be advantageous to use polycrystalline Cr:ZnSe materials to increase the optical-to-optical efficiency.

Tuning with a Lyot filter has been accomplished for a free spectral range of 0.12  $\mu\text{m}$  from the 2.23  $\mu\text{m}$  lower limit of the used Lyot filter of a 2 mm thickness up to 2.37  $\mu\text{m}$  with a relatively constant output power of more than 100 mW.

In Cr:ZnSe thin disk lasers, a thermal lensing induced, cyclic instability has been identified experimentally and theoretically. For power scaling Cr:ZnSe thin disk lasers, it is important to know the conditions for the thermal lensing induced instability to occur. In a thin disk laser design, the output power limitation by the thermal lensing induced instability can be overcome by enlarging the pump spot and still keeping the pump power density in the order of 10  $\text{kW}/\text{cm}^2$ . Comparing to a bulk laser design, a thin disk laser design has the inherent advantage of optimized cooling conditions and has therefore the potential to be power scaled into the multi 10 W range.

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