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NOVEL, COMPACT, AND SIMPLE ND:YVO_4 LASER WITH 12 W OF CW OPTICAL OUTPUT POWER AND GOOD BEAM QUALITY

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ABSTRACT

We present first, promising experiments with a novel, compact and simple Nd:YVO_4 slab laser with 12 W of 1.06 µm optical output power and a beam quality factor $M^2 \sim 2.5$. The laser is made of a diffusion-bonded YVO_4/Nd:YVO_4 composite crystal that exhibits two unique features. First, it ensures a one-dimensional heat removal from the laser crystal, which leads to a temperature profile without detrimental influence on the laser beam. Thus, the induced thermo-optical aberrations to the laser field are low, allowing power scaling with good beam quality. Second, the composite crystal itself acts as a waveguide for the 809 nm pump-light that is supplied from a diode laser bar. Pump-light shaping optics, e.g. fast- or slow-axis collimators can be omitted, reducing the complexity of the system. Pump-light redundancy can be easily achieved. Eventually, the investigated slab laser might be suitable for distortion-free high gain amplification of weak optical signals.

1. INTRODUCTION

The main requirements for diode-pumped solid-state lasers in space born applications are high reliability and efficiency, pump-light redundancy as well as high compactness and simplicity. Simultaneously, there is a strong demand for a good beam quality of such lasers in order to transmit optical information over large distances. In common solid-state rod lasers, the beam quality is affected by pump-light induced thermo-optical aberrations. This is briefly outlined in the following. The optical pump process in a solid-state laser material is closely connected with the generation of heat for two reasons. First, the energy difference between the pump photon and the laser photon is lost as heat to the host lattice. This causes the so-called quantum-defect heating. Second, the quantum efficiency of the fluorescence processes involved in the laser transition is less than unity. Thus, heating due to quenching mechanisms takes place.
In the ideal case of a homogenously pumped laser rod, the heat is generated in the interior and is removed via the cylindrical surface. Neglecting the temperature dependence of the heat conductivity of the crystal and solving the differential heat equation, one obtains a radial heat flow that leads to a perfect parabolic temperature profile within the rod. Due to the thermal dispersion of the laser material, a pump-light dependent thermal lens is set up, that finally leads to a pump-light dependent beam diameter of the laser beam inside the resonator. Eventually, this lens leads to transverse multi-mode operation at higher pump powers and thus decreases the beam quality. In principle, this thermal lens can be compensated by intra-cavity optical elements (e.g. lenses, mirrors) for a favourable working point in order to ensure a good beam quality.
In practice, neither the pump-light distribution across the rod cross-section is homogenous, nor the cooling via the cylindrical surface. The heat conductivity of the laser material usually exhibits some temperature dependence. All these deviations from the ideal case lead to a distortion of the parabolic temperature profile. These thermo-optical aberrations lead to a distortion of the laser beam wavefronts within the resonator. The wavefront distortion usually leads to higher diffraction losses and thus can decrease the output power of a laser dramatically.
Thus, engineering of high brightness solid-state lasers requires a reduction of pump-light induced thermo-optical aberrations. On one side, this can be achieved by intra-cavity adaptive optics, which is still a new and growing field in laser physics and not suitable for space born applications at this early stage. A different approach is to reduce the aberrations in the laser crystal themselves by appropriate crystal geometries with modified cooling arrangements.

2. THE THIN DISK LASER

An outstanding example for a solid-state laser with reduced thermo-optical aberrations is the architecture of the thin disk laser [1]. The gain medium is given by a very thin disk that is pumped from its front side and that is cooled from its back side (Fig. 1). This cooling arrangement leads to an almost one-dimensional axial heat flow perpendicular to the disk surface. The resulting temperature profile exhibits a parabolic dependence along the crystals rotation axis, but almost no spatial dependence along the radial direction. This leads to an almost aberration-free gain medium for the laser mode and indeed power scaling up to several tens of Watts in a diffraction limited TEM_{00} mode has been demonstrated in the past.

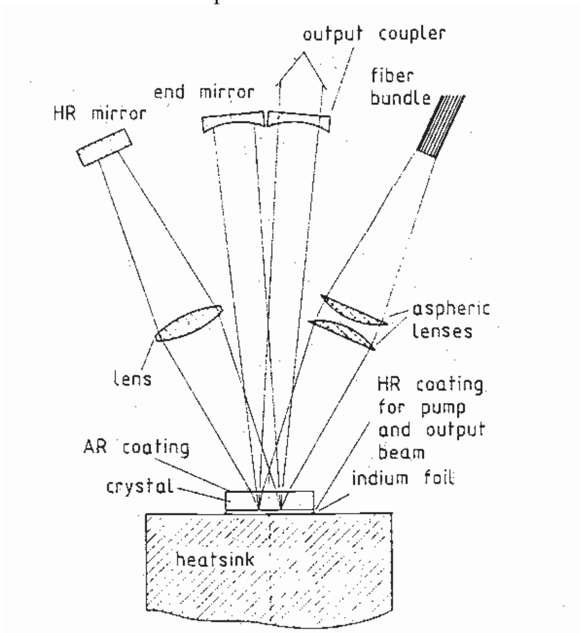

Fig. 1. Schematic cross-section of the Thin Disk laser.

However, the thin disk laser has also some drawbacks in regard to space born applications. The gain medium has a thickness of only a couple hundred microns, leading to a very small single-pass absorption for the pump-light. In order to increase the absorption efficiency, the absorption length is artificially increased by a complex pump-light folding optic. Further, the pump-light is supplied from a fibre-pigtailed diode laser. Thus, besides the folding optics, the disk laser needs a pump source that itself is very complex. Finally, the pump-light has to be focussed to a well-defined spot on disk centre, which requires precise adjustment of the folding optics and a defined position of the fibre-pigtail. Pump-light redundancy cannot be applied easily. There are still some residual aberrations in the disk laser, since only a small fraction of the disk area is pumped in order to prevent in-plane parasitic mode oscillations.

3. THE GRAZING INCIDENCE SLAB LASER

Contrary to the thin disk laser, the architecture of the diode side-pumped Grazing Incidence Slab Laser (GISL) is simple and compact [2-4]. Here, the laser beam enters the slab at an angle of grazing incidence and it experiences total internal reflection (TIR) at the surface where the pump-light is coupled into the slab (Fig. 2). The slab itself is made of a highly absorbing material, which ensures high spatial overlap of the absorbed pump-light and the laser mode, eventually leading to high conversion efficiencies.

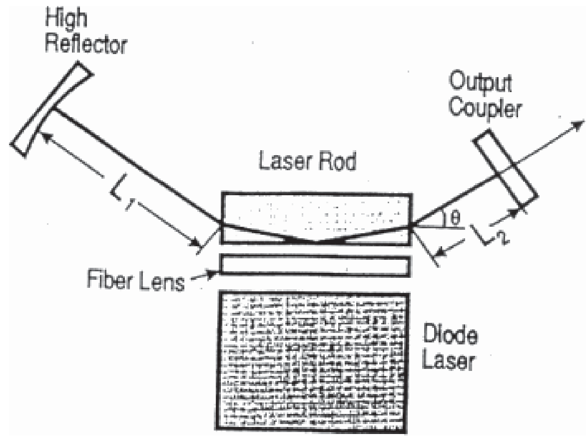

Fig. 2. Schematic top view of the Grazing Incidence Laser.

But the GISL also has some drawbacks. The diode laser bar is usually focussed into the slab by a cylindrical lens to produce a stripe-like pumped region of 50 µm x 10 mm. Contrary to the thin disk laser, in the GISL the cooling direction of the slab and the resulting temperature profile lead to an astigmatic thermal lens with strong aberrations. These aberrations reduce the conversion efficiency of the pump radiation into a TEM_{00} mode.

In the following, we present a novel slab laser, the Composite Thin Slab Laser (CTSL). It combines the property of low-aberrations of the thin disk laser with the compact and simple architecture of the GISL.

4. THE COMPOSITE THIN SLAB LASER

The basic innovations of the Composite Thin Slab Laser (CTSL) are the following: a) the diffusion-bonded composite crystal, b) the coupling and guiding of the pump-light and c) the cooling arrangement of the crystal. The crystal is made of a ~300 µm thin $Nd:YVO_4$ plate that is diffusion-bonded to an undoped YVO_4 crystal of 11 mm x 10.5 mm x 1.5 mm (Fig. 3). The pump-light of the diode laser bar is polarized parallel to the highly absorbing c-axis of the $Nd:YVO_4$ plate. Contrary to the GISL, here the pump-light is coupled at the opposite side into the undoped part of the CTSL crystal. This modified pump arrangement has two major advantages. First, it gives access to the bottom side of the doped $Nd:YVO_4$ plate, in order to remove the heat from the crystal according to the thin disk laser concept. Second, the pump-light is guided in the fast- and slow-axis by total internal reflection within the undoped part towards the attached $Nd:YVO_4$ plate. Any pump light shaping elements, e.g. fast-axis or slow-axis collimators, can be omitted. The bottom side of the thin $Nd:YVO_4$ plate is highly reflective for the pump-light at 809 nm in order to achieve double-pass absorption and to increase the absorption efficiency.

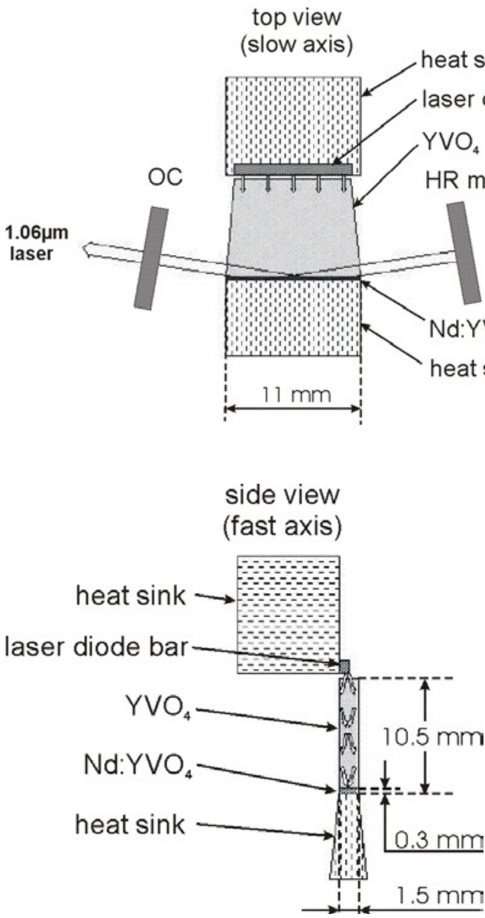

Fig. 3. Top view and side view of the CTSL

This pump arrangement leads to a smooth spatially confined gain with a low pump light intensity. Thus, the laser material is subjected to only negligible mechanical stresses. The oscillating laser mode enters the undoped YVO_4 crystal at its sides at an angle of only 5°, traverses the doped $Nd:YVO_4$ plate and is then reflected at the bottom side of the crystal. In order to ensure lossless total internal reflection (TIR) at the interface we have introduced a layer SiO_2 of ~ 1 µm thickness between the doped $Nd:YVO_4$ plate and the highly reflective coating for the pump-light. SiO_2 has a refractive index of about 1.44, whereas the refractive index of $Nd:YVO_4$ is about 1.96. Thus, the SiO_2 layer suppresses coupling losses via the evanescent field. Due to the shallow angle between the laser beam and the TIR interface, an effective gain length of 10 mm can be obtained, although the $Nd:YVO_4$ plate has a thickness of only 300 µm. Thus, despite a low pump light intensity, the small-signal gain is fairly high. The $Nd:YVO_4$ plate itself is cooled from its back side, leading to an almost one-dimensional heat-flow as it is known from the thin disk laser. The optical aberrations to the laser field are low, resulting in a laser beam of good beam quality. To review the main differences between the GISL and the CTSL the reader is referred to Fig. 4.

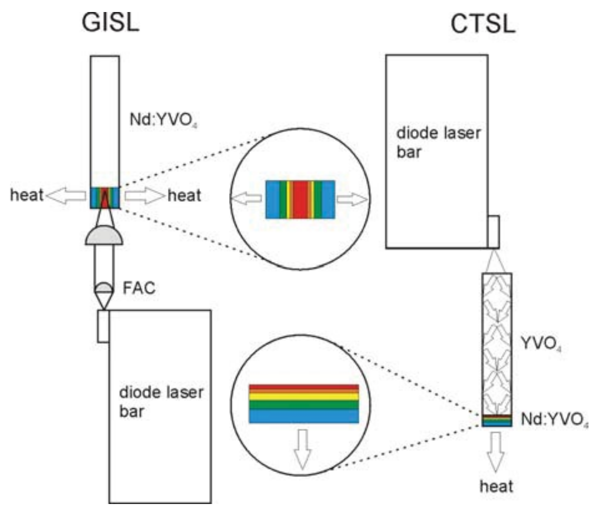

Fig. 4. Comparison of pump-light coupling, crystal cooling and resulting temperature profiles in the GISL and the CTSL.

Due to the side-wise cooling, the GISL exhibits a parabolic temperature distribution that leads to a strong cylindrical thermal lens. Since the laser beam enters the crystal in the orthogonal plane at an inclined angle, it experiences astigmatism. Contrary, the CTSL is cooled at its bottom side, leading to a homogenous temperature distribution with parallel isotherms within the crystal. This temperature profile induces almost no thermo-optical wavefront aberrations to the laser beam. In a ray tracing model this can be explained, as shown in Fig. 5.

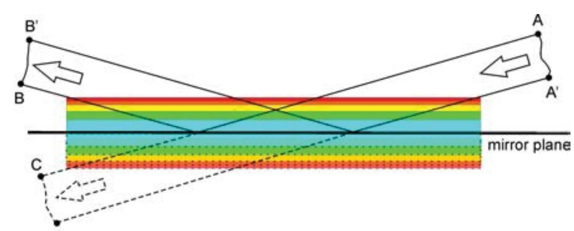

Fig. 5. Temperature profile in the CTSL.

Instead of ray tracing that is subject to TIR along the paths AB or A'B', one can consider the equivalent physical case where the temperature profile is mirrored at the reflection interface. Now, the true rays AB and A'B' are replaced by the virtual rays AC and A'C', respectively. For this case it is evident, that the rays experience exactly the same temperature distribution along their propagation direction z. Each of them has the same optical path length (OPL), because the integrals in (1) are equal. Here dn/dT is the thermal dispersion of the laser crystal.

$$OPL = \frac{dn}{dT} \cdot \int_A^C T(z)dz = \frac{dn}{dT} \cdot \int_{A'}^{C'} T(z)dz \qquad (1)$$

Any ray that propagates with the same angle of incidence between AC and A'C' has also the same OPL. This means that for a bundle of incoming rays the optical path difference between each ray is always zero. Since the rays are perpendicular to the incoming wavefront, there is no wavefront distortion associated with the propagation through the temperature profile of the CTSL.

5. LASER EXPERIMENTS

For a very first demonstration of the Nd:YVO_4 CTSL we have set up a simple plan-concave resonator with 120 mm mirror spacing. The radius of curvature of the highly reflective mirror is 2 m, and the optimum reflectivity of the plane output coupler is 85 %. The pump-light is supplied by a 40 W Jenoptik water-cooled diode laser bar that is polarized in the fast-axis. The CTSL crystal is glued to a gold coated heat sink that is attached to a thermo-electric Peltier cooler. In Fig. 6 one can see the diode laser bar on the right side and the mounted CTSL crystal on the left side. The pumped 300 µm thin Nd:YVO_4 plate is recognized by the strong fluorescence region closely to the heat sink.

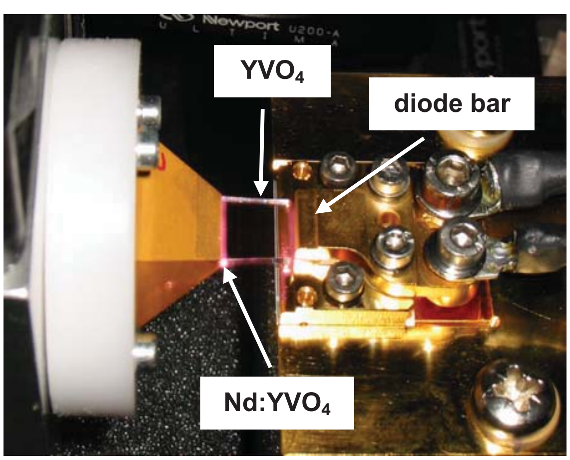

Fig. 6. Laboratory set-up of the CTSL

First preliminary experiments demonstrate a cw output power of almost 12 W with a beam quality factor of $M^2 \sim 2.5$ (Fig. 7). The optical slope efficiency is about 38 %. Further improvement of the beam quality will be achieved with appropriate resonator configurations.

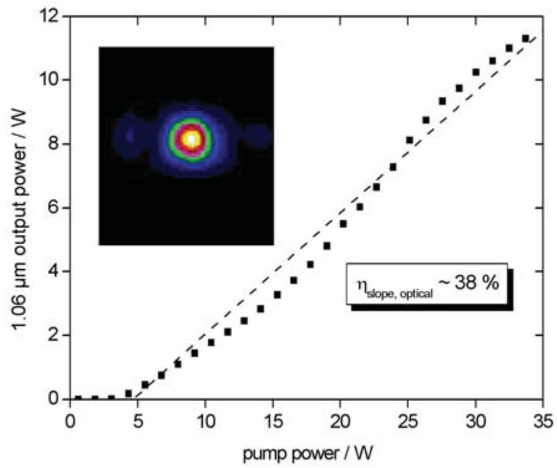

Fig. 7. Output power characteristic of the CTSL.

We determined the intra-cavity losses *V* and the small-signal gain g_0 from a Findlay-Clay diagram by changing the reflectivity *R* of the output coupler, in order to investigate the performance of the CTSL for the amplification of weak signals for optical free-space communications (Fig.8).

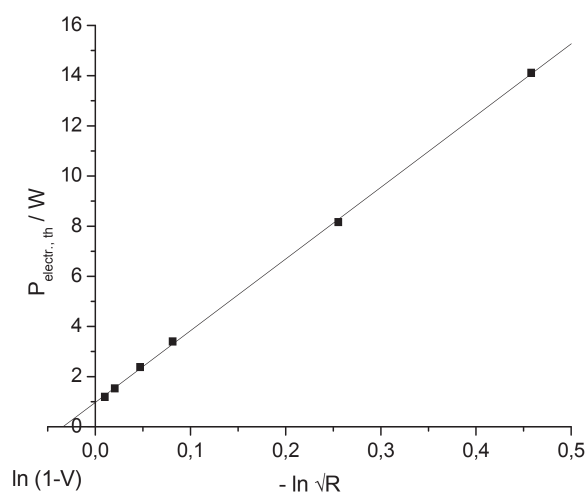

Fig. 8. Findlay-Clay measurement.

The resonator losses are mainly induced by diffraction at the crystals aperture and are measured to be about 3 %, whereas the single-pass small-signal gain is determined to be $G = exp(g_0 l) \sim 7$. In order to confirm the estimated single-pass small-signal gain, we have set up a CTSL amplifier experiment.

6. AMPLIER EXPERIMENTS

The laser to be amplified is a Nd:YAG monolithic nonplanar ring laser (NPRO) [5] with a free spectral range of 8 GHz. It has a maximum TEM_{00} single-frequency output power of 200 mW at a centre wavelength of 1.06 µm with a very high frequency and amplitude stability. The oscillator beam is adjusted to a $1/e^2$ mode diameter of 1 mm in order to prevent diffraction effects at the 1.5 mm aperture of the CTSL. The CTSL has been seeded with different oscillator output powers of 50 mW, 100 mW, and 200 mW (Fig. 9).

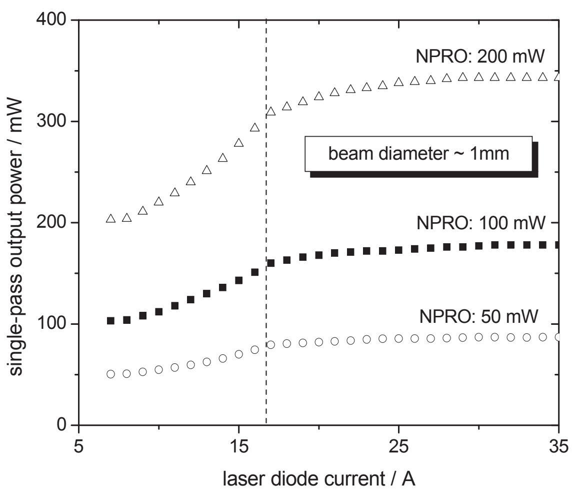

Fig. 9. Single-Pass amplification in the CTSL.

For low pump currents of the CTSL diode laser bar, the amplification shows an exponential behaviour for any NPRO seed power. At a pump power, corresponding to a diode laser current of about 16 A, the amplification begins to clamp. This clamping cannot be explained by the well known gain saturation. In case of 300 mW of single-pass output power, the intensity of the laser beam within the CTSL crystal is < 50 W/cm^2. This intensity is much smaller than the saturation intensity of Nd:YVO_4 of 890 W/cm^2. Thus, there must be another explanation for the output power clamping. We think that parasitic modes oscillate the CTSL crystal and compete with the gain that is necessary to amplify the NPRO seeder. In the laser experiments, the effects of parasitic modes effects could not be observed, because the intra-cavity intensity was much larger. Thus the gain was strongly saturated by the laser beam, leaving almost no residual inversion for a parasitic mode.

To scale the amplifier to higher output powers, we are currently working on possibilities to suppress the oscillation of parasitic modes within the crystal. This will be done by roughening some crystal surfaces in order to induce high losses to the parasitic mode. Then, the CTSL could also serve as a compact and simple distortion-free laser amplifier for free-space communications.

7. CONCLUSION

We introduced a novel, simple and compact solid-state laser, the Composite Thin Slab Laser (CTSL). Due to a novel pump-light and cooling arrangement, the pumped crystal induces almost no thermo-optical aberrations to the laser field. Since the laser crystal itself acts as a waveguide for the pump-light, no pump-beam shaping optics are required. We investigated the CTSL in laser- and amplifier-operation. While the laser is operating nicely, we still have problems with parasitic mode oscillation that reduces the efficiency in the amplifier set-up. We expect to solve these problems in the near future.

8. REFERENCES

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