2-µm $Tm:Lu_2O_3$ ceramic disk laser intracavity-pumped by a semiconductor disk laser

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Abstract: A proof-of-principle study of a 1.97-µm $Tm:Lu_2O_3$ ceramic disk laser, intracavity pumped by a 1.2-µm semiconductor disk laser, is presented. The demonstrated concept allows for improved pump absorption and takes advantage of the broad wavelength coverage provided by semiconductor disk laser technology. For thin disk lasers the small thickness of the gain element typically leads to inefficient pump light absorption. This problem is usually solved by using a complex multi-pass pump arrangement. In this study we address this challenge with a new laser concept of an intracavity pumped ceramic thin disk laser. The output power at 1.97 µm was limited to 250 mW due to heat spreader-less mounting scheme of the ceramic gain disk.

OCIS codes: (140.3380) Laser materials; (140.5680) Rare earth and transition metal solid-state lasers; (140.5560) Pumping; (140.5960) Semiconductor lasers; (140.7270) Vertical emitting lasers.

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1. Introduction

Near infrared light sources emitting in the eye-safe region of the spectrum at around 2-µm wavelengths, where absorption by atmospheric constituents such as water vapor and CO_2 takes place, are needed in global environmental monitoring, long-range LIDARs, medical diagnostics, laser surgery, materials processing, and many other emerging applications [1–3]. Tm-ions can provide emission at wavelengths spanning from 1.8 um to 2.1 um, depending on the host crystal [4]. Tm-doped Lu_2O_3 crystals are capable of efficient laser action at 2 µm when pumped at 808 nm with commercial multimode diode modules [5].

In comparison to single crystals, ceramic materials possess stronger fracture toughness and their doping levels can be varied more freely [6]. Moreover, ceramics can be manufactured industrially in large volumes into a given shape and size [7,8]. The material properties and the consequent increased life-time and resistance to laser induced damage make ceramics promising gain materials for high-power lasers as well as for short pulse generation [9,10].

Recently, a Tm-doped Lu_2O_3 ceramic laser was demonstrated [11]. With diode pumping at 808 nm, 26 W of output power and 33% optical-to-optical conversion efficiency was obtained from the ceramic rod in continuous wave (CW) regime at 2066 nm. In a subsequent study, a similar rod laser was mode-locked with a semiconductor saturable absorber mirror, confirming the applicability of the Tm:Lu_2O_3 ceramic medium to sub-picosecond pulse operation [12].

In this study, we present a proof-of-principle demonstration of a Tm-doped Lu_2O_3 ceramic disk laser. Disk geometry of the gain element has several advantages over rod geometry, including power scaling without compromising beam quality and the possibility to generate ultrashort pulses at high average power levels [13,14]. The advantages of the disk geometry originate from the increased ratio of cooling surface to pumped volume as compared to rod design and the decreased interaction length of the light passing through the gain element. The first diode-pumped Tm:Lu_2O_3 single crystal disk laser was reported by M. Schellhorn et al. [15]. The Tm:Lu_2O_3 ceramic disk laser is intra-cavity pumped with a semiconductor disk laser (SDL). SDLs can cover a broad wavelength range from ultraviolet to mid-infrared region and intrinsically operate with open high-Q cavities into which intracavity optical elements can easily be integrated for efficient frequency conversion or precise control of the laser output [16–20]. The inefficient pump absorption typical for a solid-state gain disk with small thickness can be overcome using multiple pass pump recycling through the disk [21]. In such a pumping scheme, pump optics repeatedly re-image the pump spot on the gain disk.

The resulting multiple pump beam passes through the gain medium lead to enhanced pump light absorption. The intricate multipass pump focusing system can be replaced by an intracavity pumping scheme [22]. The main advantage of the intracavity pumping scheme is the natural multiple-pass propagation of the pump laser beam through the gain medium. Therefore, in contrast with external pumping, a very thin gain disk with low doping level can be used. The demonstrated pumping concept can be applied to achieve high pump intensities for gain materials with low single-pass absorption or absorption lines inaccessible with traditional diode pump lasers. The presented $Tm:Lu_2O_3$ ceramic disk laser operated without extensive thermal management, which limited the output power at 2 µm to 250 mW.

2. Ceramic gain disk, SDL and experimental setup

The $Tm:Lu_2O_3$ ceramic disk, manufactured by Konoshima Chemical Co., had 2-at.% Tm^{3+} concentration, a diameter of 3 mm and thickness of 260 µm. The disk was mounted between two water-cooled copper plates to prevent thermal problems. Indium foil placed between the sample and copper alleviated mechanical stress and ensured reliable contact to the heat sink. The copper plates had apertures with 1.5-mm diameters for the SDL and ceramic laser light. Dielectric antireflection coatings were deposited on both surfaces of the ceramic disk to allow low-loss propagation of the SDL light at a small angle (<15°) to the surface normal of the sample. The targeted reflectivity of the coated sample surface was <0.1% at 1.2 µm and <4% at 2 µm. The temperature of the copper mount was kept at 15 °C during the experiments.

Figure 1(a) shows transmission of the ceramic disk at 8° angle to the surface normal, measured with a spectrophotometer in the range 1.1 – 1.3 µm. The beam of the white-light source was partially blocked by the aperture in the sample holder, resulting in small transmission values. The vertical axis in Fig. 1(a) has been rescaled with the help of well-known absorption cross section data for $Tm:Lu_2O_3$ ceramic that predict nearly complete transmission at 1.1 µm [11]. It can be seen that absorption has a local maximum at 1.2 µm, corresponding to the $^3H_6 \rightarrow {}^3H_5$ transition. The cross-section of this transition is about 2 times higher than that of the $^3H_6 \rightarrow {}^3H_4$ transition used for 800 nm pumping [11]. The transitions corresponding to pumping in the 1200-nm wavelength band and at 800 nm are depicted in Fig. 1(b). With pumping at 1200 nm, the upper laser level $^3F_4$ of the 2-µm laser transition is populated by a non-radiative transition $^3H_5 \rightarrow {}^3F_4$, resulting in a four-level scheme. Contrary to pumping at 800 nm, a cross-relaxation process is not involved for 1.2-µm pumping. Theoretically, when pumped at 800 nm, Tm-doped lasers can achieve an optical-to-optical efficiency close to 80% through a process in which every absorbed pump photon excites two Tm atoms [23]. Therefore, the quantum defect is slightly higher for 1200-nm pumping compared to pumping the upper laser level $^3F_4$ via the cross-relaxation process. However, the optical-to-optical efficiencies demonstrated so far with $Tm:Lu_2O_3$ ceramic or crystal lasers have not reached the predicted efficiency for the cross-relaxation process and has been limited to about 40% for diode pumping [5,11]. One reason for this might be the high doping level required for an efficient cross-relaxation process, which may deteriorate the crystal quality and result in reduced optical and thermal parameters of the crystal.

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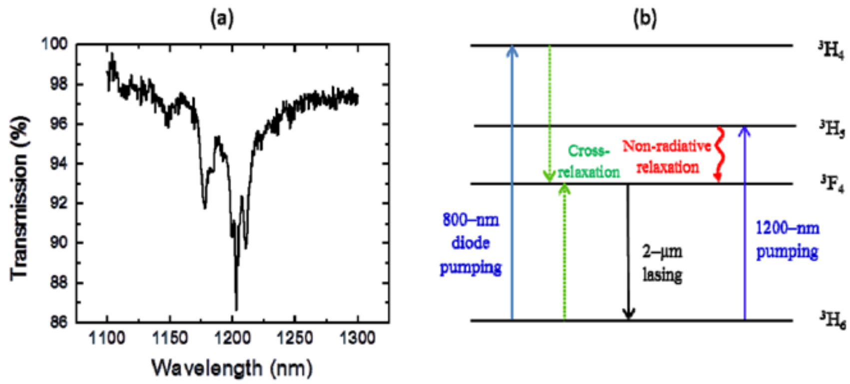

Fig. 1. (a) Transmission of the ceramic Tm:Lu_2O_3 disk. (b) Energy diagram of Tm:Lu_2O_3 ceramics showing 800-nm and 1200-nm pumping transitions.

The gain element of the semiconductor disk laser was grown in a single step by molecular beam epitaxy. The gain structure consists of ten InGaAs quantum wells strain compensated by GaAsP spacer layers, and a 23-layer pair AlAs/GaAs DBR. The subcavity formed between the sample surface and the bottom DBR, which arises from the Gires-Tournois etalon-like nature of the gain element [16], was designed to be antiresonant for the operation wavelength of 1180 nm in order to enhance wavelength tunability of the SDL. The detailed structure of the SDL gain chip has been described elsewhere [24]. The chip was mounted on a diamond heat spreader by means of flip–chip technology [25] and the diamond was bonded with indium to a water-cooled heat sink kept at 20 °C during experiments.

The experimental setup used in the study is shown in Fig. 2. The 1.2-µm semiconductor disk laser has no output coupling other than absorption in the Tm:Lu_2O_3 ceramic disk. The ceramic disk has its own cavity and produces a laser beam at a wavelength of 1.97 µm. The SDL gain mirror was pumped by 808-nm radiation from a fiber-coupled multimode diode laser module focused onto a spot of about 400 µm in diameter. A V-shaped cavity was built with two spherical high reflective (HR) mirrors for the 1.2-µm SDL. The ceramic disk was placed inside the SDL cavity at a location where the SDL transversal mode diameter was around 340 µm. The disk was tilted 15° from the perpendicular position to allow a linear cavity for the 2-µm light to be set up with two spherical mirrors, one of which was partially reflective (PR) for outcoupling the 2-µm radiation. The diameter of the transversal mode of the 2-µm laser was about 250 µm at the ceramic disk to ensure complete overlap of the mode and the 1.2-µm SDL beam.

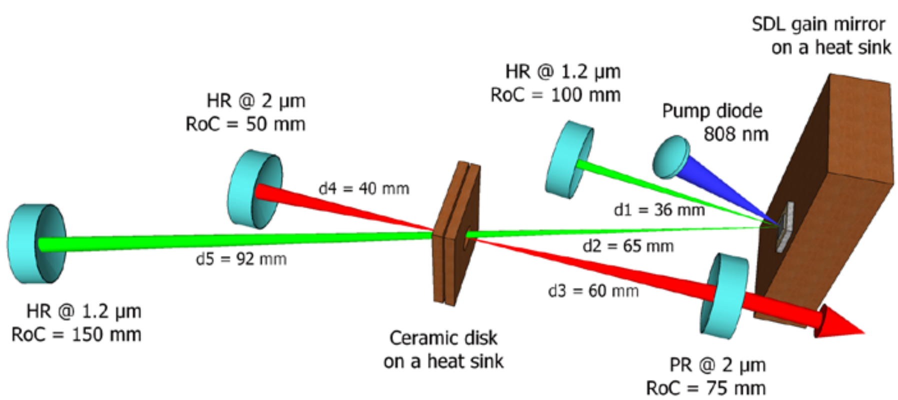

Fig. 2. Experimental setup. The SDL cavity is sketched in green and the ceramic disk laser cavity in red. HR –high reflective, RoC –radius of curvature, PR –partially reflective.

3. Experimental results

Output power of the $Tm:Lu_2O_3$ ceramic disk laser measured with various output couplers (OCs) as a function of the diode pump power incident on the SDL gain chip is shown in Fig. 3. The output power was limited by thermal roll-over to 250 mW for 1.2-% outcoupling. 5.2-% slope efficiency with respect to diode pump power was achieved with the 1.2-% OC of the ceramic disk laser. Since the pumped gain area has no direct thermal contact with the heat sink surface, the temperature at the center of the pumped area can rise more than one hundred degrees above room temperature for pump powers used in the experiment, according to our simulations performed with COMSOL Multiphysics software. A decrease of gain with temperature is likely to limit the output power performance, as was observed in previous studies for $Tm:Lu_2O_3$ single crystal thin disks [15]. It is clear that the laser in its present configuration is not power scalable because of the inefficient heat removal from the pumped gain area. With the ceramic gain disk properly mounted on an adequate diamond heat spreader, substantial power scaling could be expected. The roll-over of output power was accompanied by thermal lensing. Readjustment of the cavity alignment and length was required in order to restore good quality beam profile and stability of the output power of the ceramic disk laser at high pump power levels. The intracavity power of the SDL at 1160 nm is plotted in Fig. 3 (right vertical axis) for the ceramic disk laser outcoupling of 1.2%.

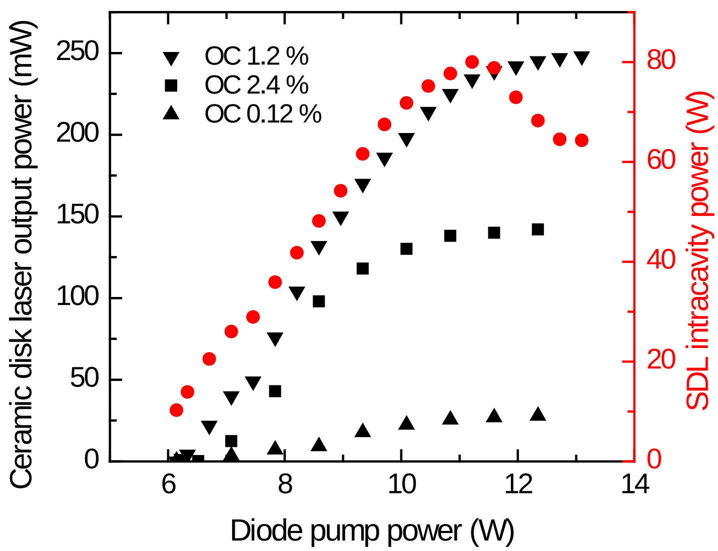

Fig. 3. Output power of the 2-µm ceramic disk laser with different output couplers (OCs) (in black, left vertical axis) and optical power circulating in the SDL cavity at 1160 nm with 1.2-% OC of the ceramic laser (red dots, right vertical axis) as a function of the diode pump power. The SDL intracavity power was evaluated from the light leaking through one of the HR mirrors of the SDL cavity. Changes in the wavelength of the SDL (and thus in absorption by the ceramic disk) contribute to the shapes of the output curves.

The small irregularities in the output power of the ceramic disk laser with respect to diode pump power are caused by changes in the SDL spectrum that have an effect on the 1.2-µm light absorption in the ceramic disk material. As can be seen in Fig. 1, absorption of the $Tm:Lu_2O_3$ ceramics increases when the wavelength is shifted from the local absorption minimum at 1160 nm to longer wavelengths closer to the absorption peaks at around 1200 nm. An increase in the multimode diode module power results in a redshift of the SDL wavelength and in an increase in the absorption of pump power for the ceramic disk laser. The redshift can be observed also in Fig. 4(a) showing the optical spectrum of the SDL at various power levels. The changes in absorption of the SDL light in the ceramic disk in turn

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affect the SDL intracavity power. The decrease in the SDL intracavity power at high pump powers, seen in Fig. 3 (right vertical axis), doesn't cause a corresponding drop in the output power of the ceramic disk laser because of the increase in absorption of the SDL light. We measured single pass absorption of about 1.5% at 1160 nm for the ceramic disk, which is in good agreement with the absorption cross section data measured for $Tm{:}Lu_2O_3$ ceramics [11]. Taking into account that light travels in a cavity in two directions we can estimate that the maximum absorbed pump intensity at 1160 nm was about 26 W/mm^2. The optical spectrum of the ceramic disk laser measured close to lasing threshold and at the maximum output power is presented in Fig. 4(b). The discrete lines in the spectrum are due to the etalon effect caused by reflections at the ceramic/air interfaces. The inset shows the output beam profile measured with a pyrocamera at the maximum output power of the ceramic disk laser.

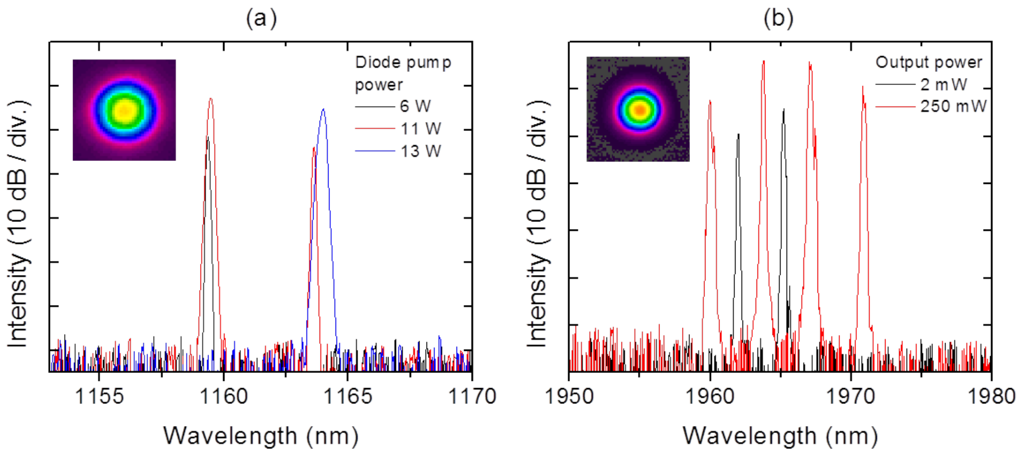

Fig. 4. (a) Spectrum of the SDL at various diode pump powers. (b) Ceramic disk laser spectrum at output powers of 2 and 250 mW. Beam shapes at maximum output powers measured with a pyrocamera are shown as insets in (a) for the SDL and in (b) for the ceramic disk laser.

4. Discussion

It should be noted that output power of a few hundred milliwatts was obtained even without extensive thermal management applied. The output power from the ceramic disk could be scaled up by reducing the heat load imposed on the sample, for example by attaching a heat spreader onto the disk. The presented conceptual test experiments for intracavity pumping the ceramic disk with the 1.2-µm SDL were carried out without transparent diamond heat spreaders to study the influence of quantum defect without disturbances that may arise from etalon effects associated with multiple reflections from the diamond/sample interfaces and surfaces of the diamond. Mounting the disk in direct contact to heat spreaders on one or both sides will be tested in future experiments to reduce thermal lensing and the risk of thermally induced damage of the ceramic disk.

The ceramic gain material used in the experiments was originally designed to be operated in bulk/rod form rather than in disk configuration. Therefore, further power scaling can be expected by optimizing the doping level, thickness and material quality of the ceramic disk. For example, lower concentration of Tm ions would decrease absorption losses for the SDL cavity and allow tuning the intracavity pumping wavelength from 1160 nm to 1200 nm. Lower doping level may decrease defect density and improve optical quality of the material, which could contribute to lower losses and reduced heating of the disk and result in higher output powers. The increased absorption at 1200 nm compared to that at 1160 nm would permit to decrease the thickness of the ceramic disk while maintaining adequate single pass absorption, thereby facilitating more efficient heat removal from the ceramic gain element. Considerable changes in the doping level can be implemented when the ceramic is pumped at

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1.2 µm instead of 800 nm where high ion concentration is required for efficient cross-relaxation process [4, 23].

5. Conclusion

A 1.97-µm Tm:Lu_2O_3 ceramic disk laser intracavity pumped by a semiconductor disk laser was demonstrated. The described intracavity pumping scheme allows elevate pump absorption in the thin gain disk, eliminates the need for a complex multi-pass system usually applied for pumping thin disks and takes advantage of the broad wavelength coverage provided by semiconductor disk laser technology. The Tm:Lu_2O_3 ceramic disk laser produces 250 mW of CW output power limited by thermal roll-over in the heat spreader-less assembly. Using disk geometry considerable power scaling can be expected with proper thermal management and optimized doping level of the ceramic gain medium.

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