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Received March 30, 2012; revised May 28, 2012; accepted June 1, 2012;
posted June 1, 2012 (Doc. ID 165601); published July 11, 2012

We demonstrate an Yb:YAG single-crystal fiber laser with 251 W output power in continuous-wave and an optical efficiency of 44%. This performance can be explained by the high overlap between pump and signal beams brought by the pump guiding and by the good thermal management provided by the single-crystal fiber geometry. The oscillator performance with a reflectivity of the output coupler as low as 20% also shows high potential for power amplification.

OCIS codes: 140.3615, 140.3480.

High-average power pulsed lasers are widely used in materials processing. Above 100 W of average power, diode-pumped Yb-doped solid-state lasers implemented in master oscillator power amplifier configuration clearly dominate this field of application with pulse durations ranging from picoseconds to femtoseconds. However, closer investigations indicate that different technologies can be used, each having individual advantages and drawbacks. Optical fiber lasers have proven to be very efficient and to enable high output powers in the continuous-wave regime with up to several kW of output power in fundamental mode operation. However, due to the strong signal confinement, their use is limited by the damage threshold of the facets and nonlinear effects such as stimulated Raman scattering, self-phase modulation, and self-focusing in the pulsed regime [1]. The thin-disk technology does not exhibit this limitation in the pulsed regime but suffers from relatively low axial gain limited by amplification of spontaneous emission in the transverse direction gain due to the crystal geometry [2], leading to limited energy per pulse and to complex multipass or regenerative amplifier setups. Finally, the slab technology has recently shown clear competitive advantages with over 1 kW of average output power obtained in the subpicosecond regime and 80 MW peak power [3]. Its drawback is the complexity of the signal beam propagation through the gain medium. Therefore, simple and versatile high power amplifiers for pulsed operation are still an ongoing subject of research.

In this Letter, we show that single-crystal fibers are a promising alternative to these technologies. A single-crystal fiber is an end-pumped long and thin-rod laser with beam guiding only for the pump radiation. This concept provides a good thermal management thanks to the high thermal conductivity of Yb:YAG and the high surface-to-volume ratio offered by the relatively thin and long rod geometry. Moreover, it enables the use of low brightness laser diodes in combination with a long crystal thanks to pump guiding.

Up to now, a maximum of 65 W of output power in continuous-wave has been demonstrated using an Yb: YAG single-crystal fiber at a pump power of 200 W at 940 nm [4]. This concept has started to reveal its potential as a femtosecond amplifier with a combination of high gain (30) and significant output power (12 W) in a very simple double-pass configuration [5]. In this Letter, we report on an exploration of the step further in terms of power scaling and report on the performance of an Yb:YAG single-crystal fiber oscillator pumped at 600 W with a fiber coupled laser diode at 940 nm. Furthermore, we discuss the potential of this technology for its use as a power amplifier.

The crystal fiber used in our experiments has a length of 40 mm and a diameter of 1 mm. With a low doping concentration of 1%, the distribution of the thermal load over the comparatively long rod together with the small transverse dimension of the rod reduces the temperature increase in the gain medium. Finite element analysis indicates that the small distance between the edge of the crystal and the center results in maximum temperature increases as small as 46 K for 600 W of incident pump power when using a 1 mm diameter 40 mm long crystal with 90% overall absorption and a 600 μm pump spot diameter launched into the crystal. The same temperature difference for a more conventional 3 mm diameter rod would be more than two times higher and amount to 117 K. Whereas the gradient inside the central volume of the crystal stays the same, the temperature difference between the edge and the center is strongly dependent on the crystal section.

Low doping concentration and small transverse dimensions are not the only parameters to limit the temperature increase: the quality of the thermal contact between the gain medium and its cooled mount may be a key issue as well. As reported in [4], the thermal contact was responsible of 80% of the total temperature difference between the crystal center and the mount in a single-crystal fiber surrounded by thermal grease in a nonoptimized mount. The Laboratoire Charles Fabry and Fibercryst have worked together to develop an excellent metallic contact in the single-crystal fiber TARANIS modules [6]. This is discussed in detail in [7]: a temperature difference between the crystal edge and the module of below 5 K has been measured for 86 W of incident pump power at 808 nm on a 0.2% doped Nd:YAG.

The pump guiding in the single-crystal fiber allows increasing the overlap between the pumped beam and the signal beam in free propagation when compared to

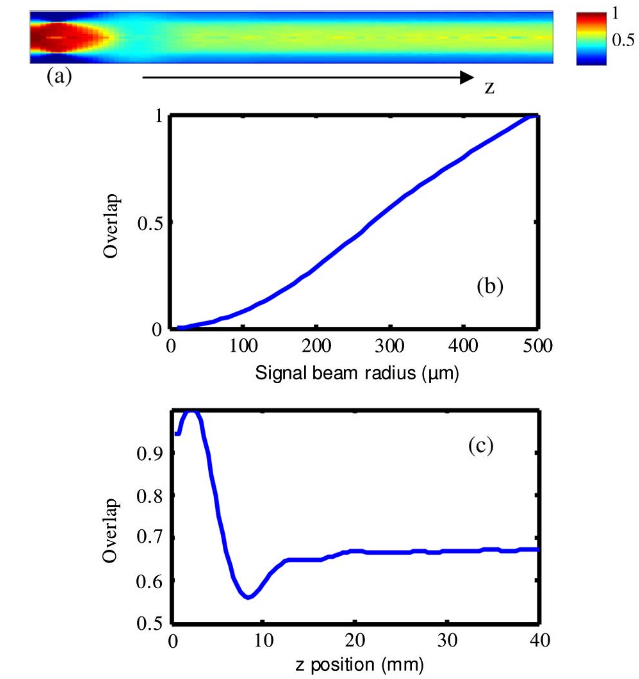

Fig. 1. (Color online) (a) Pump intensity distribution normalized by the maximum of intensity for each z position for a 1 mm diameter 40 mm long single-crystal fiber; (b) total geometrical overlap between the pump beam and a flat-top signal beam as a function of the signal beam radius; (c) geometrical overlap between the pump beam and a 700 μm diameter flat-top beam as a function of the axial position.

standard bulk technology. Using ray tracing analysis, we obtained the pump intensity distribution in the fiber normalized by the maximum of intensity for each z position. It shows clearly higher intensity in the central area of the crystal brought by the pump guiding in the right part [Fig. 1(a)]. This normalized pump intensity was calculated for an NA of 0.22 and a pump diameter of 600 μm at the entrance face of a single-crystal fiber of 1 mm diameter. The geometrical overlap between a flat-top signal beam and the pump beam is given as a function of the signal beam radius in Fig. 1(b). It shows that up to 69% of overlap can be obtained for a signal beam diameter of 700 μm, which covers 70% of the total rod radius.

Figure 1(c) shows, in each plane along the propagation axis, the overlap between the pump beam and a flat-top signal with 700 μm diameter corresponding to the experimental conditions described in the following. The overlap first increases until the focal point is reached [see Fig. 1(a)] and starts decreasing afterwards until it reaches a minimum of 56% at a distance of about 9 mm from the entrance face of the fiber, corresponding to a position where major part of the pump beam is reflected on the fiber surface. For the last 20 mm of fiber length, the overlap remains almost constant with a value of 67%. Considering a 90% overall absorption, we have calculated the overlap increase to be 2.3 times higher than what would be obtained in the same configuration without pump guiding.

In order to explore the potential of the single-crystal fiber in terms of power scalability, a simple two mirror cavity design has been used. As shown in Fig. 2, the

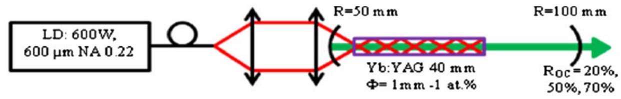

Fig. 2. (Color online) Experimental setup.

single-crystal fiber was placed in between a meniscus with a radius of curvature of 50 mm and an output coupler with a radius of curvature of 100 mm. The distances "meniscus to crystal" and "crystal to output coupler" were respectively 20 and 85 mm. A fiber coupled diode laser emitting at 940 nm with 600 μm core diameter, an NA of 0.22, and a maximum output power of 600 W was used for optical pumping. The fiber output was imaged onto the crystal with a 1:1 magnification ratio using two aspheric lenses of 50 mm focal length. The TARANIS module provided by Fibercryst contained a 40 mm long and 1 mm diameter Yb:YAG single-crystal fiber (1% doping) placed in a $3 \times 40 \times 70$ mm^3 copper block. Both crystal faces had an antireflective coating with 0.2% reflectivity. With a pump absorption around 90%, reabsorption losses at the laser wavelength have a negligible impact since the end of the crystal reaches transparency for an incident pump power around 100 W. Thermal bonding between the crystal and the copper block was ensured by a metallic contact. We estimate that the heat transfer coefficient is around 5 W/cm^2/K, which is approximately five times better than what can usually be obtained using an indium foil. Mechanical stresses induced by the bonding were sufficiently low to maintain a depolarization below 0.4%. Two copper microchannel plates and carbon foils were used to cool the module. The mounts of the aspheric lenses and the mirrors were water cooled in order to limit the temperature increase of the optics due to possible residual absorption. A dichroic mirror was used to filter out the residual pump power for the output power measurement.

The output power as a function of the incident pump power was measured for three different output couplers having reflectivities of 20%, 50%, and 70%. A maximum output power of 251 W was measured for an output mirror reflecting 70% and at an incident pump power of 570 W resulting in an optical efficiency of 44%. The slope efficiency was measured to reach 53%. To the best of our knowledge, this is the highest efficiency ever measured in a single-crystal fiber laser. As shown in Fig. 3, no rollover is visible on the efficiency curve, showing that further power scaling should be possible. Finite element analysis indicates that the pump power limit before fracture should be at 1 kW for one pumped face.

The beam profile at full pump power is shown in Fig. 3. We measured a beam quality factor M^2 of about 15. This high value can be explained by two factors. Firstly, due to the lower brightness of the pump beam, no soft aperture mode filtering occurs, as observed previously [4]. Secondly, the cavity design was not fully optimized and we believe that the use of a larger resonant fundamental mode would result in an improvement of the beam quality.

The lowest reflecting mirror (Roc = 20%) can give an idea of the potential of the gain medium as power amplifier. Neglecting passive losses, laser oscillation with this mirror means that the active medium provides a

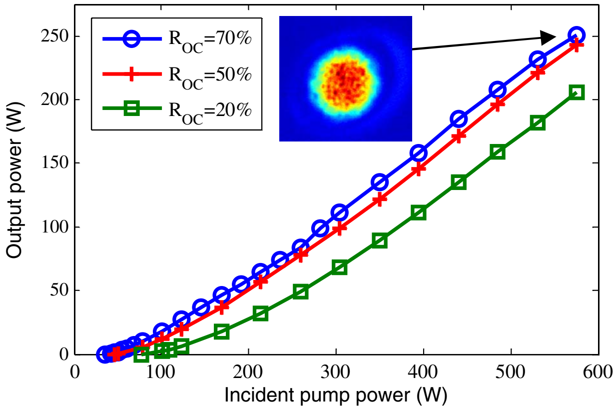

Fig. 3. (Color online) Efficiency curves.

saturated round-trip gain of 5. At maximum pump power, the output power of 200 W (Fig. 3) means that the gain medium amplifies the intracavity beam from 50 W (the fraction of power reflected by the 20% output coupler) to 250 W in one round-trip. This reveals the high potential of single-crystal fiber technology providing both high gain and significant extraction efficiency for power amplifier design. In order to study the impact of the intensity profile on extraction efficiency, we modelized our single-crystal fiber amplifier using a similar method to what is described in [8]. Two cases were considered for the signal: a 700 μm diameter flat-top beam and a 500 μm Gaussian beam. For a pump power of 600 W and an input signal of 50 W, we found an output power of 258 W for the flat-top beam and 216 W for the Gaussian beam. This small difference is due to high saturation of the gain in the case of power amplification. This shows that good extraction efficiency can be expected even for high quality signal beams.

In conclusion, we have demonstrated the potential of the single-crystal fiber technology for the high power regime with more than 250 W of output power obtained out of an Yb:YAG continuous-wave laser. To our knowledge, this is the present power record, exceeding previous results reported on single-crystal fibers by a factor of 4. The optical efficiency of up to 44% and a slope efficiency of 53% represent the highest efficiency ever achieved with a single-crystal fiber laser. The analysis of the performance obtained with a low reflecting output coupler indicates that a power amplifier boosting power from 50 W to 250 W in a two-pass configuration should be feasible with this Yb:YAG single-crystal fiber. This proves that the way is open towards simple and efficient power amplifiers in the "100 W class" for Yb:YAG single-crystal fibers.

Xavier Délen acknowledges the French DGA for the funding of his Ph.D.

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