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High-power laser with Nd:YAG single-crystal fiber grown by the micro-pulling-down technique

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We present optical characterization and laser results achieved with single-crystal fibers directly grown by the micro-pulling-down technique. We investigate the spectroscopic and optical quality of the fiber, and we present the first laser results. We achieved a cw laser power of 10 W at 1064 nm for an incident pump power of 60 W at 808 nm and 360 kW peak power for 12 ns pulses at 1 kHz in the *Q*-switched regime. It is, to the best of our knowledge, the highest laser power ever achieved with directly grown single-crystal fibers.

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A laser medium that would benefit from the spectroscopic and thermomechanical advantages of bulk crystals and from the pump guiding and the good heat load repartition of doped glass fibers would be ideal for high-average-power and high-peak-power laser systems. This leads to the design of crystal fibers: long and thin crystals with a low doping concentration and pump-guiding properties to dispatch the heat load along the active medium. To manufacture such fibers, various methods have already been investigated. It is possible to shape a Czochralski (Cz) rod like a fiber, but it is a costly method that needs a lot of cutting and polishing, and the fiber diameter usually stays above a few millimeters. Nevertheless, such systems demonstrated good laser results.[1] It is also possible to use ceramic materials, which allow for a precise engineering of the fibers, and a core-clad structure has already been presented in ceramic Nd:YAG.[2] The main drawback of this technique is the high cost and equipment necessary to obtain samples with good optical quality. To avoid reshaping or costly manufacturing, it would be better to directly grow single-crystal fibers with a simpler growth process. The micro-pulling-down[3] (μPD) and laser-heated pedestal growth[4] (LHPG) are the two usual methods to manufacture such fibers. Recent publications were presented with Nd:YAG (Ref. 5) and Nd:YVO$_4$ (Ref. 6) crystal fibers grown by LHPG, and with Yb:YAG (Ref. 7) and Nd:YAG (Ref. 8) crystal fibers grown by μPD. In both cases, to the best of our knowledge, no multiwatt efficient laser system was ever presented because of the low optical quality of the fibers. We recently presented[9] the growth of high-quality Nd:YAG single-crystal fibers by an advanced μPD technique, suitable for laser applications.

With this growing technique, it is possible to grow up to 1 m long single-crystal fibers, with a diameter going from 0.3 to 1 mm. The growth process is not limited to YAG crystals, and many other matrices have already been realized (e.g., LiNBO$_3$, Al$_2$O$_3$, BGO). The method is low cost and highly reliable concerning the crystal quality. The cylinder quality is good enough for optical guiding without any additional polishing. X-ray diffraction measurements on the fibers are in perfect agreement with the tabulated results of a Y$_3$Al$_5$O$_{12}$ phase, demonstrating the quality of the raw material made from Y$_2$O$_3$ and Al$_2$O$_3$ powders. Laue diffraction was used to check if the crystal orientation in the $\langle 111 \rangle$ axis was in good agreement with the seed orientation. X-ray topography reveals no defect in μPD-grown crystals such as those observed in Cz-grown crystals of the same dimensions. The emission spectrum of the single-crystal fiber was obtained under excitation by using a pulsed dye laser at 750 nm. Results are plotted in Fig. 1. The observed spectrum is in good agreement with the one of a Cz-grown bulk crystal measured in the same conditions. We also checked the upper laser level lifetime, and values of 240 μs were measured in both crystal fibers and a Cz bulk crystal, in good agreement with the literature. For all the experiments, we used 50 mm long and 1 mm diameter samples, with an antireflective coating at 1064 nm on both faces. A doping concentration of 0.2% at. in Nd^{3+} was measured in the fibers. To evaluate the guiding efficiency of the pump inside the fiber, we injected the output beam of a fiber-coupled laser diode (NA=0.2) at 980 nm (this wavelength is outside the Nd^{3+} absorption) thanks to two doublets. By comparing the input and output powers, we deduced an overall guiding efficiency of 90%, including the insertion losses. Those measurements were carried out within crystal fibers coming directly from the growth process, without any additional polishing of the cylinder.

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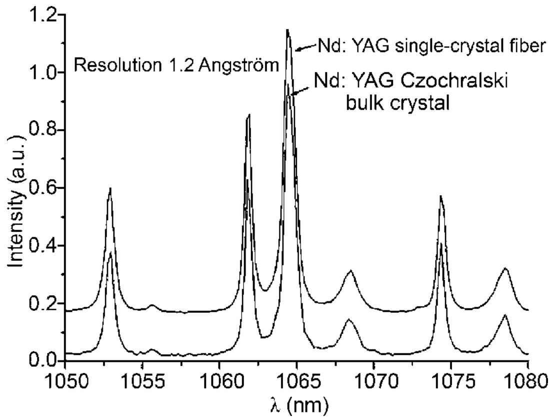

Fig. 1. Emission spectrum of a Nd:YAG single-crystal fiber and a bulk crystal (resolution, 0.12 nm).

A transmission better than 99% was also measured in those samples (without any guiding effect) thanks to a probe beam at 1064 nm with a beam diameter of 300 μm, confirming their good optical quality. Even if the transmission is good, wavefront distortion inside the crystal fiber, caused by local refractive index inhomogeneity, might deteriorate laser emission. To investigate the wavefront distortion, we used a Shack–Hartmann analyzer (HASO64 Imagine Optic Inc.). The beam of a He–Ne laser at 633 nm was sent through the fiber without being guided. The beam was slightly focused so the beam waist has a diameter of 250 μm. Figure 2 presents the wavefronts recorded with a 50 mm long Nd:YAG Cz-grown bulk crystal, and with a 50 mm long and a 1 mm diameter single-crystal fiber grown by μPD. The incident wavefront is almost perfectly plane ($\lambda/100$ rms). The wavefront measured after the Cz crystal is plane at $\lambda/40$ rms, and the wavefront measured after the crystal fiber is still plane at $\lambda/10$ rms. Those measurements show that the wavefront deformations introduced by the single-crystal fibers are relatively slight, so they should not notably affect the laser performances.

We achieved laser operation in the cw and Q-switched regimes under diode pumping to demonstrate the laser potential of single-crystal fibers. The experimental setup is shown in Fig. 3. We used a copper mount with water cooling to remove the heat. The crystal fiber was simply placed in a notch cut inside the mount, with thermal grease to ensure a good heat transfer. The fiber was longitudinally pumped by a fiber-coupled laser diode with a maximum output power of 60 W at 808 nm. The core diameter of the diode fiber was 400 μm with a NA of 0.2. The pump was injected inside the crystal fiber thanks to two identical doublets. We observed pump guiding inside the fiber, and we measured an absorption coefficient of 0.72 cm^{-1}, resulting in a good heat load repartition along the fiber length. Laser emission was achieved inside a 18 cm long two-mirror cavity. Simulations with a Gaussian beam propagation software predicted a laser waist of 250 μm located near the middle of the fiber (the laser signal is not guided in the fiber). The output mirror had a transmission of 40% at 1064 nm and a radius of curvature of 100 mm.

We measured the pump power threshold to deduce the losses introduced by the single-crystal fiber in the cavity by theoretical calculations. We found a loss coefficient of 0.6 cm^{-1}, corresponding to 3% single-pass losses. Those losses are higher than the 1% losses found in direct transmission, because they take into account more parameters such as wavefront distortions and higher diffraction losses (the laser mode is larger than the probe beam). The cw laser efficiency is plotted in Fig. 4. We achieved a maximum output power of 10.2 W at 1064 nm for an absorbed pump power of 54 W. We measured a slope efficiency of 22% and a beam quality factor $M^2=5$. To better understand those results, we made laser power simulations. As we used high-transmission output couplers, we used the Rigrod[10] formalism to achieve our calculations. We included the calculated diffraction losses at both faces of the crystal fiber in the simulation. With a fiber introducing 3% losses inside the cavity, the simulations give a maximum laser power of 11.5 W for 60 W of launch pump power, with an optimum output coupler of 38% and an optimum beam

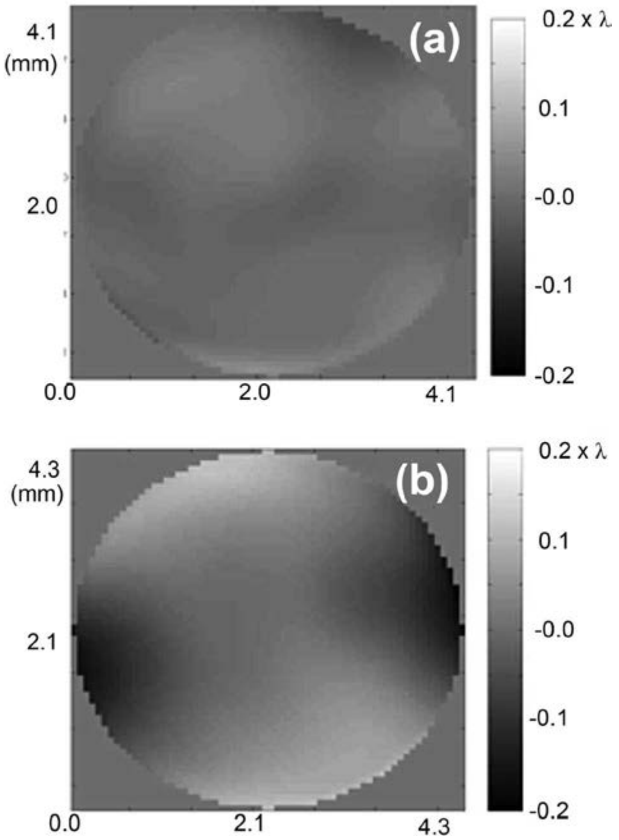

Fig. 2. Wavefront deformation measured after (a) a bulk crystal and (b) a single-crystal fiber grown by μPD ($\lambda=633$ nm).

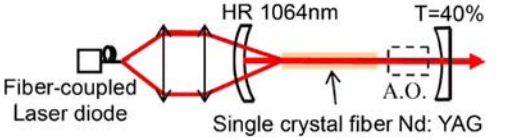

Fig. 3. (Color online) Experimental setup.

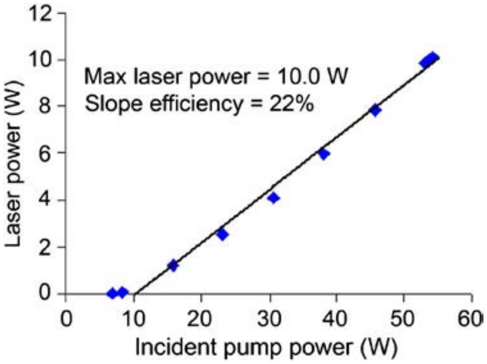

Fig. 4. (Color online) Laser efficiency in cw operation at 1064 nm.

waist of 250 μm. All those values are coherent with our experimental results. With a perfect fiber, introducing no losses inside the cavity, the calculated maximum laser power is ~15 W. Those results can seem uncompetitive: with typical commercially available bulk Nd:YAG crystals (a few millimeters long and a doping concentration ~1%), laser-diode end-pumped systems achieved slope efficiencies above 50%, with a diffraction-limited output, for laser powers at approximately tens of watts.[11] Nevertheless, single-crystal fibers can withstand higher pump powers and therefore reach higher laser powers. Moreover, the efficiency of our system is not limited by the crystal quality but by the mismatch between the pump and the laser mode. In our setup, the pump is guided into the fiber, whereas the laser mode is not guided but defined by the cavity design. Therefore the size of the laser mode inside the crystal fiber must be large enough to have a good overlap with the pump dispatched in all the fiber diameter and small enough to avoid diffraction losses due to the small diameter of the gain media. This effect limits the slope efficiency. Moreover, as the fundamental laser mode is always smaller than the pump mode, the remaining population inversion is available for higher-order modes, leading to M^2 superior to unity. The compromise between a good overlap with the pump and low diffraction losses is the main limitation of the laser efficiency until now. To solve this issue, it would be necessary to add an undoped YAG cladding around the doped fiber. It would then be possible to achieve a perfect overlap between the laser mode and the gain area with no diffraction losses. This would lead to better laser efficiency and better mode quality.

Finite-element analysis simulations were also carried out to evaluate the thermal management improvement in single-crystal fibers compared with bulk crystals. We simulate a typical Nd:YAG bulk crystal, 3 mm × 3 mm × 10 mm, with a doping concentration of ~1%. We took into account a heat transfer coefficient of 2.0 W/cm^2 K between the crystal and its mount, corresponding to a typical good-quality cooling system. For a pump power of 60 W focused on a spot of 400 μm diameter, the simulation gives a maximal temperature of 215 °C and a stress intensity of 140 MPa. This stress intensity is closer to the typical fracture limit than can be found in the literature for YAG crystals.[12] Consequently, in this configuration, the risk of damaging the crystal is very high. Comparatively, a 1 mm diameter and a 50 mm long single-crystal fiber under the same pump power with the same cooling system would reach a maximum temperature of 60 °C and a stress coefficient of 18 MPa, thus showing a far better thermal management. In the single-crystal fiber, the maximum stress intensity withstood by the YAG is reached for a pump power of approximately 500 W, indicating the upper limit of our system in terms of pump power.

The Q-switched regime was achieved with an acousto-optic modulator inserted inside the oscillator. Because of a very short cavity ($L = 17$ cm), we achieved 12 ns pulses with a repetition rate of 1 kHz and an average power of 4.4 W. This leads to an energy of 4.4 mJ per pulse and a peak power of 364 kW. Such peak power and pulse duration are difficult to achieve in usual fiber lasers, because of cavity length and nonlinear effects, showing the potential of single-crystal fibers for high-peak power and high-average power oscillators and amplifiers.

To conclude, the recent evolution of the μPD growing technique makes it a low-cost solution to grow nearly ready-to-use single-crystal fibers with good optical quality. We demonstrated efficient laser oscillation in the cw and Q-switched operations, and we investigated the potential of this promising laser medium for high-power lasers.

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