IOP Publishing | Astro Ltd Laser Physics Letters
Laser Phys. Lett. 13 (2016) 075101 (4pp) doi:10.1088/1612-2011/13/7/075101

Highly efficient waveguided laser performance of diode pumped unclad Yb:YAG crystalline fibre

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Received 4 April 2016
Accepted for publication 29 April 2016
Published 26 May 2016

Abstract
Single crystal fibre (SCF), as most often used in the literature today, is the term referring to a relatively thin (under 1 mm diameter) and pretty short (30–60 mm long), unclad single-crystalline rod surrounded by air, in a laser configuration where the pump power is waveguided by the total internal reflection of the cylindrical circumference. In previous reports on SCF lasers the pump is flood-illuminating the volume of the gain medium, while the generated laser signal is in a free propagation mode inside the laser rod, i.e. the laser mode structure is defined solely by the external cavity mirror configuration. Presented here are the experimental laser results obtained with the diode-pumped, 100 μm diameter, 100 mm long, unclad Yb:YAG crystalline fibre, wherein both pump light and generated laser power are waveguided. To the best of our knowledge, the demonstrated laser operation is based on the thinnest and the longest unclad fibre reported so far. It is also believed to be the first reported true waveguided laser operation from an unclad single crystalline fibre. Laser efficiency of over 58% obtained with no antireflective coatings on fibre ends is a manifestation of low composite loss figure, inclusive of both material bulk and waveguiding loss.

Keywords: fibre laser, diode-pumped laser, crystalline fibre, waveguided propagation

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser power scaling out of a single laser aperture (as opposed to power scaling via power combining from multiple laser apertures) is one of the most important technology development directions in both bulk solid state and fibre laser technologies. The most prominent recent trend in fibre laser technology aiming at major power scaling out of a single laser aperture is transitioning from all-glass double- and triple-clad fibres to fully-crystalline double- and triple-clad fibres. It has been perceived lately as a major next step in fibre laser development, with the projected advancement in power scaling with diffraction limited beam quality by at least an order of magnitude out of single fibre aperture [1, 2]. A few demonstrations toward that end, based on fully crystalline, relatively short, square cross-section, fibre-like waveguiding structures fabricated using the adhesive-free bonding (AFB) technique [3], provided sufficient basis for favouring fully crystalline structures versus conventional all-glass structures [4–6]. Despite these demonstrations, the AFB-based fully-crystalline double- and triple-clad fibre fabrication technique is deemed way too labour-intensive and, thus, not amenable for mass producible fibre fabrication. In contrast to that, recent successes in producing high quality, long and smooth, round crystalline fibre cores using laser heated pedestal growth (LHPG) technique were recognized as promising for mass production (pending development of equally mass-producible crystalline cladding deposition technique). So far, quite impressive laser results with glass-clad doped crystalline YAG cores, grown by LHPG, were obtained (e.g. [7, 8]).

Figure 1. Simplified optical layout of the laser experimental setup. A ~100 mm long, 1% Yb doped YAG crystalline fibre is free-space-pumped by a laser diode module at ~969 nm. Crystalline fibre diameter is 100 μm.

Unfortunately, glass-clad double-clad fibres lack the required potential for power scaling due to the glass clad functioning, essentially, as pretty thick thermal insulator around the crystalline core. To the best of our knowledge, the fully-crystalline double-clad LHPG-grown fibre has not been reported as lasing (or amplifying) so far, namely due to major challenges in developing high optical quality crystalline cladding. Those challenges are not believed to be insurmountable, and quite a few efforts in developing techniques for high optical quality crystalline cladding deposition on the cylindrical circumference of LHPG-grown crystalline cores are ongoing (e.g. [9, 10]). Meanwhile, major improvement in optical quality of the LHPG-grown fibre cores themselves is still required. In the process of perfecting crystalline core fabrication via LHPG, in order to scale the fibre core length with highest optical quality, the fibre quality assessment using just straight-through laser light propagation (representative of bulk material loss only) is no longer sufficient. Fibre core quality assessment should be complemented by experiments which can be indicative of low waveguiding loss as well. In that sense, laser experiments utilizing crystalline fibres as gain medium can be adequate. Experiments with single crystal fibres (SCF), as most often used in the literature today [11], where the 'SCF' term is referring to only relatively thin (under 1 mm diameter) and pretty short (30–60 mm long), air-clad single-crystalline gain element (rod) in a laser configuration where only the pump power is guided by the total internal reflection (TIR) of the cylindrical circumference are not adequate for that. Indeed, in most reports on SCF lasers the pump is flood-illuminating the volume of the gain medium, while the generated laser signal is in a free propagation mode inside the laser rod, so the laser mode structure is defined solely by the external cavity mirror configuration [11–13]. This mode of laser operation does not involve waveguiding of the laser light, and, thus, is not indicative of a waveguiding quality of the SCF core. Presented here are experimental laser results obtained with the diode-pumped at 969 nm, 100 μm diameter, 100 mm long, unclad Yb:YAG crystalline fibre, wherein both the pump light and the generated laser power are waveguided. To the best of our knowledge, the demonstrated laser operation is based on the thinnest and the longest unclad crystalline fibre reported so far. It is also believed to be the first true waveguided laser operation reported from an unclad single crystalline fibre. Laser efficiency of over 58% obtained from the studied fibre, despite its use without the antireflective (AR) coatings on laser quality polished tips, is a manifestation of low composite loss figure, inclusive of both material bulk and waveguiding loss.

2. Experimental setup

The Yb:YAG crystalline fibres for our experiments were grown using an LHPG technique from ceramic YAG feed rods prepared from YAG powder with the desired dopant level. The detailed fibre growth procedure is described in [9]. Post growth, the fibres were annealed in a high temperature oven in air. The oven temperature was ramped up at a rate of 5 °C min^{-1} to a temperature of 1000 °C, kept at this point for twelve hours, and then ramped down to room temperature. Following the annealing, the tip of each fibre was placed inside a close fitting glass capillary tube and polished with the 'ULTRAPOL End and Edge' polisher to a laser grade surface quality on both fibre end faces.

Figure 1 presents the simplified experimental laser setup. A linearly polarized 969 nm laser diode module with a spectral bandwidth of ~3 nm and a free-space collimated output was coupled into a crystalline fibre by a Lens 1 (focal length $f_1 = 15$ mm) through the plano–plano dichroic mirror M1 (highly transmissive for the pump wavelength and highly reflective in the vicinity of the Yb:YAG laser wavelength at 1030 nm). A 100 mm long, dia. 100 μm, 1% Yb-doped YAG unclad crystalline fibre, with no AR coatings on the laser grade polished tips, has been placed freely in a v-groove of a copper base attached to the *xyz*-alignment stage. We intended to laser-test the unclad fibre with both the pump and the generated laser light waveguided by the TIR of the as-grown crystal fibre interface with the ambient air. Thus, in order to eliminate possible frustration of the TIR, we used neither thermal grease nor other means of pump-induced heat removal, so absolutely no cooling was provided to the fibre. For that reason, the laser diode module was run in a quasi-continuous (Q-CW) mode with the pump duration of 1 ms and the pulse repetition frequency of 10 Hz. Given the duty cycle of only 1%, at 100 W of absorbed operating pump power the fibre would only be subjected to 1 W of absorbed average power, so there is no fibre overheating. It is worth noting here that with the Q-CW 'pump on' duration of 1 ms commensurate with the upper laser level lifetime of Yb^{3+} in YAG (~1 ms), the operating regime of Yb:YAG laser is physically equivalent to the CW regime in all aspects, but with significantly reduced thermal load. So our results obtained with the Q-CW pumping are fully representative of a CW operating regime in terms of output power and efficiency which could be obtained with the adequate laser fibre cooling. The laser cavity is comprised of two plano–plano mirrors M1 and M2, each positioned not more than 1–2 μm from the fibre ends. In this case the end

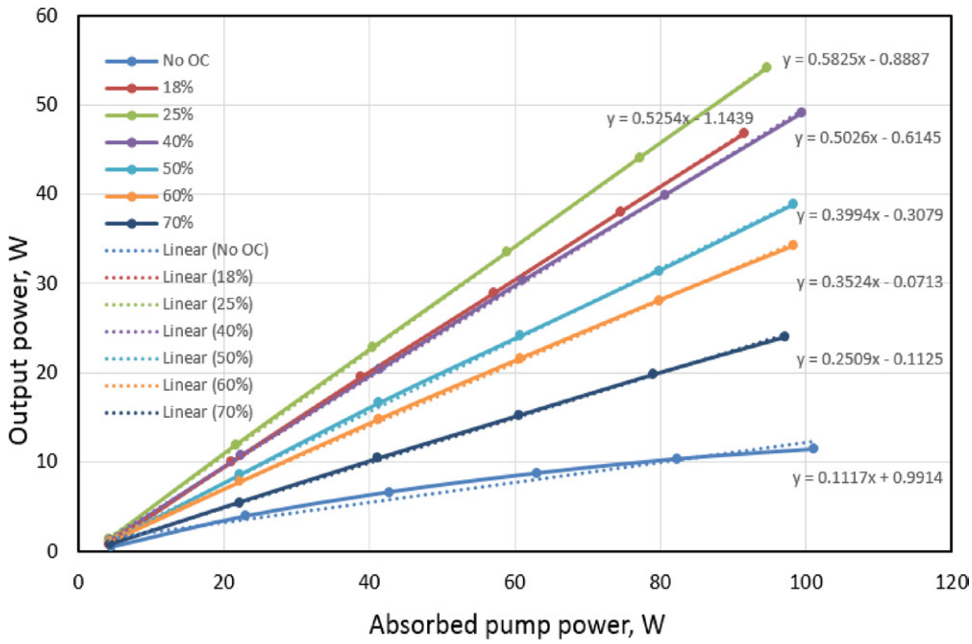

Figure 2. Yb:YAG fibre laser output power (Q-CW) at 1030 nm versus absorbed diode laser pump power at 969 nm for different output couplers.

mirrors were used solely to provide the feedback required for laser operation rather than for cavity mode formation. The output mirror reflectivity was varied between 18% and 70%, and one of the experimental points has been obtained with the cavity formed by the end mirror M1 and the Fresnel reflection of the output fibre end (~8.4%). Lens 2 ($f_2 = 50$ mm) is used to collimate highly multimode and highly divergent output of the fibre laser before the longpass Filter (tilted dichroic mirror), which nearly fully transmits at 1030 nm and fully reflects at 969 nm. Lens 3 ($f_3 = 150$ mm) collects the laser output within the power meter window.

3. Experimental results

Figure 2 shows the measured Q-CW output power at 1030 nm from the waveguided laser operation of the straight (unbent) unclad single crystalline Yb:YAG fibre versus the absorbed diode laser pump power at 969 nm. Seven colour coded plots are representing data sets obtained with different output coupler reflectivities (specifically indicated in the plot legend). Dots are the experimental data sets for each output coupler reflectivity, with the lines indicating linear regression of the experimental data with the regression results noted near each data plot.

It is important to emphasize that we were able to obtain essentially the same results, such as presented in figure 2, when the measurements were carried out with the same unclad single crystalline Yb:YAG fibre intentionally bent to the bend diameter of ~30 cm. This serves as a straightforward direct confirmation of the true waveguided nature of the observed laser operation.

Figure 3 indicates the results of the output coupler reflectivity optimization for achieving maximum laser efficiency. It presents the Q-CW output power of the waveguiding laser

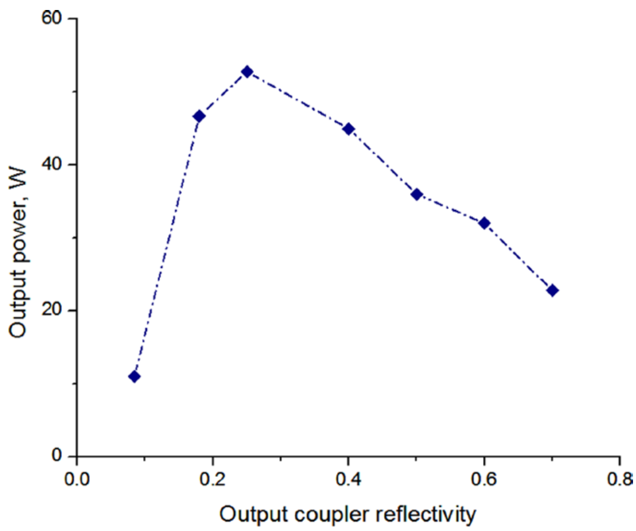

Figure 3. Laser output power (Q-CW) versus output coupler reflectivity measured at pump power of 91.6 W. The plot clearly indicates the optimum reflectivity as 25%. Connecting lines are only used as a guide to the eye.

based on the unclad LHPG Yb:YAG fibre with respect to the output coupler reflectivity at 1030 nm, where the standalone 8.4% reflectivity point (Fresnel reflection of the flat Yb:YAG fibre tip) corresponds to the case of laser operation without the output coupler. All data points are shown at the pump power of 91.6 W, for which data were available for all seven output coupler reflectivities. The output coupler reflectivity values used for plotting the dependence presented in figure 3 are simply the measured output mirror reflectivities and do not have any corrections for the interference effects between the output coupler and the uncoated output fibre tip. These corrections could be useful, but we were having difficulties in achieving consistency due to high laser operation sensitivity to mirror alignment.

The attempted Findley–Clay analysis [14] of the intracavity loss value has proven to be inconclusive due to the excessive scattering of the experimental points near the laser threshold. We believe, this is due to the cavity alignment challenges in the proximity of the crystalline fibre tips, and the lack of AR coatings on the polished fibre ends (causing some highly alignment-sensitive Fresnel-to-mirror interference effects). Nevertheless, very low laser threshold and high laser efficiency, along with the relatively low optimal output coupler reflectivity, obtained with the fibre gain element with no AR coatings, are indicative of low composite intrinsic loss figure (bulk material loss + waveguiding loss) of the LHPG-grown Yb:YAG fibre used in our experiment.

4. Conclusions

We report what is believed to be the first true waveguided laser operation of an unclad rare-earth-doped single-crystalline fibre. The results were obtained with the diode-pumped, 100 μm diameter, 100 mm long, unclad Yb:YAG crystalline fibre, wherein both pump light and generated laser power were waveguided. To the best of our knowledge, it is the thinnest and the longest unclad crystalline fibre reported to lase so far. Diode-pumped laser efficiency of over 58% obtained with the fibre having no AR coatings is a manifestation of low composite loss figure, inclusive of both material bulk and waveguiding loss.

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