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Invited Paper

Monocrystalline materials for high-power ultrafast lasers

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ABSTRACT

Crytur is a company with long tradition of growing and processing crystals for technical applications, with history reaching back to 1943. Recently we have developed Crystal Improved Growth (CRIG) method for production of large core-free single crystals of YAG. The diameter currently achieved is 140 mm (in case of undoped crystal), and the crystal weight is up to 10 kg. The method was used to grow un-doped YAG crystals, YAG:Ce crystals for large scintillating screens, and Yb:YAG and Nd:YAG for high power solid-state laser systems.

Large laser slabs were manufactured from Yb:YAG doped crystals for Diode-Pumped Solid State Laser (DPSSL) system Amos, which operates within Extreme Light Infrastructure in the Czech republic (ELI Beamlines). The dimension of the largest Yb:YAG laser slab produced is 120×120×8 mm, there is no visible stress under crossed polarizers and the wavefront distortion in the clear aperture region is smaller than λ/10 (λ=633 nm) in its Peak-to-Valley value. The edges of the slab are from diffusively bonded Cr:YAG cladding in order to suppress ASE (Amplified Spontaneous Emission).

In 2018 the performance of three sets of laser slabs (ø55x5 mm) with differently realized ASE suppression was characterized at cryogenic temperatures at HiLASE Centre in terms of small signal gain measurements as well as amplification test under 30 J pumping at 1 Hz and 10 Hz repetition rates. We provide data that show that the crystal slabs have comparable properties to the ceramic slabs (produced by Konoshima company, Japan) currently in use at HiLASE.

Keywords: monocrystals, Yb:YAG laser slabs; Diode Pumped Solid State Laser

1. INTRODUCTION

The high energy diode pumped solid state lasers (DPSSL) have emerged with the progress in development of diode stacks in the 21st century. The 1000 W operation (>100 J,10 Hz) of nanosecond DPSSL was demonstrated in 2016 at laser system Bivoj at HiLASE Centre in the Czech Republic[1]. This laser system is based on amplification of initial laser pulses from Yb doped fibre laser (operation wavelength 1030 nm) in four steps. The last two steps have Yb:YAG slab architecture and are cooled down to cryogenic temperatures by helium gas flow[2]. Currently, the ceramic Yb:YAG slabs are used in cryogenic amplifiers.

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The development of DPSSL high energy laser facilities has been followed by the search of alternative gain media. The monocrystalline Yb:YAG laser slabs were designed for system Amos (ELI beamlines) in close cooperation with Crytur, Ltd.. In system Amos the cryogenic cooled DPSSL laser serves as pump laser for Optical Parametric Chirped-pulse Amplification (OPCPA) system, with planned output: 15 fs, 20 J, 1 PW pulses at the repetition rate of 10 Hz[3].

The both laser systems Amos and Bivoj follow the DiPOLE 100 concept and were built in cooperation with Science & Technology Facilities Council, Great Britain.

The three sets of four monocrystalline Yb:YAG laser slabs (ø55x5 mm) with different ways of ASE suppression were tested in the first cryogenically cooled amplification stage of the laser system Bivoj at HiLASE Centre. The results show that ceramic and monocrystalline laser slabs provide comparable properties and that the design of ASE suppression is crucial.

2. CRYSTAL GROWTH

The Yb:YAG crystals were grown using the new improved crystal growth patented technology (CRIG), which enables production of YAG crystals without central growth defect[4]. Raw materials of high chemical purity (yttrium oxide 99.999%, ytterbium oxide 99.99%, aluminum oxide 99.999%) were sintered and melted. The crystals were grown on precisely XRD oriented crystal seeds by pulling from the melt, the conditions in furnaces were computer controlled, see Figure 1. In the case of Yb:YAG the diameter of 140 mm was reached, see Figure 2. Crystals grown by this method experienced less stress and have excellent quality without core region, see Figure 3.

Figure 1. Crystal growth pullers built by Crytur Ltd..

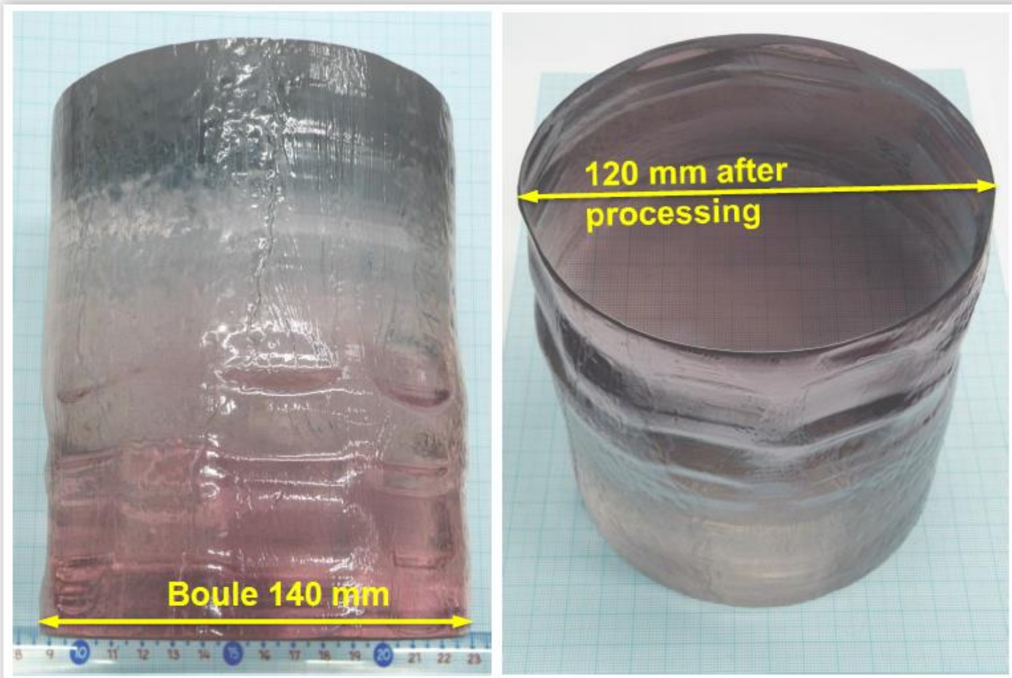

Figure 2. Yb:YAG laser quality monocrystals.

3. YB:YAG LASER SLABS

Slices with <100> orientation were cut from the Yb:YAG monocrystals and inspected, see Figure 3. The largest produced laser slab had dimensions 120x120 mm. In order to absorb the ASE the edges of this slab were created from four pieces of diffusively bonded monocrystalline Cr:YAG material. The reached wavelength distortion in transmission was <λ/20 (at 1030 nm) in its peak to valley value within the operating aperture, see Figure 4. Slabs were coated with antireflexive layers by e-beam evaporating of dielectrics.

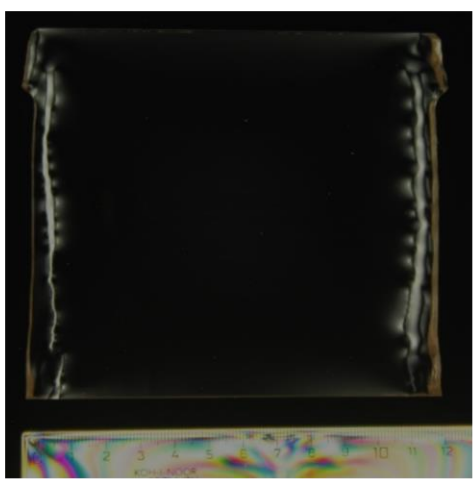

Figure 3. Stress free slice of Yb:YAG crystal. Picture taken under crossed polarizers, size 100*120 mm.

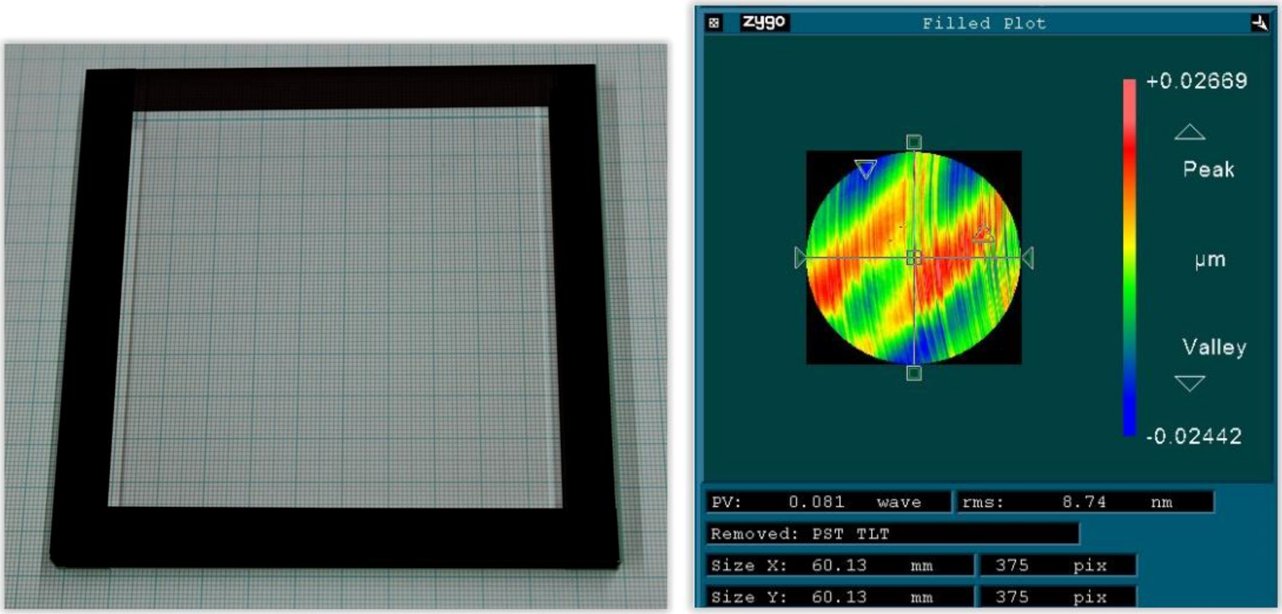

Figure 4. (left) Picture of Cr:YAG cladded monocrystalline Yb:YAG laser slab of size 120x120 mm. (right) Result of the transmitted wavelength distortion measurement of the element, used wavelength 633 nm.

Three sets of four monocrystalline laser slabs were manufactured for the first cryogenic amplification stage of the laser system Amos. The sets differed in the way of elimination of ASE. In Figure 5 representative slabs from each set are displayed. One set was plain without any ASE absorption medium. The second set had diffusively bonded Cr:YAG cladding in hexagonal symmetry (six pieces of Cr:YAG monocrystals were subsequently attached to the Yb:YAG cores of each slab). The last set had ASE solution realized by circular shape microstructures. All slabs have antireflexive coating and were checked by the scanning method in the laser resonator setup[4].

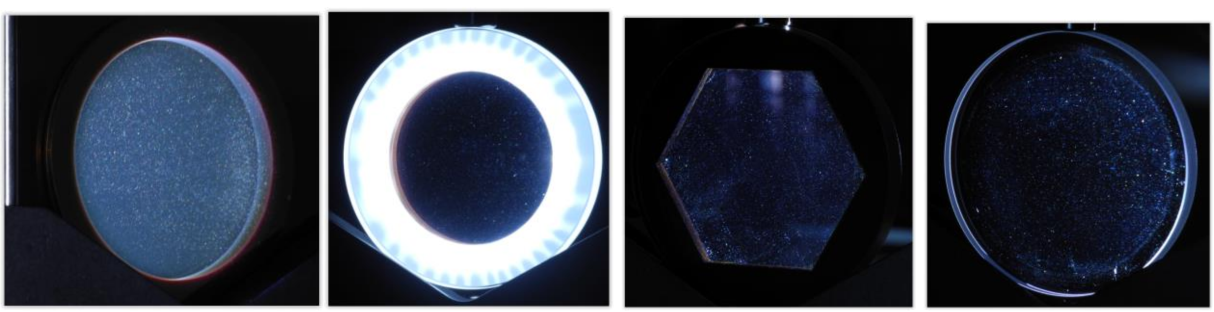

Figure 5. Yb:YAG laser slabs (ø55x5 mm) under inspection with bright light. (From left to right) Yb:YAG-Cr:YAG co-sintered ceramic slab from Konoshima company; monocrystalline slab with ASE structure from Crytur; monocrystalline slab with hexagonal Cr:YAG cladding from Crytur; plain monocrystalline slab from Crytur

4. TESTING OF LASER SLABS

All the laser disks were inspected under bright light (computer projector, divergence 15 deg.). Although all discs showed scattering pattern (Figure 5), no further influence on performance was observed. Two tests were realized in Bivoj

DPSSL system at HiLASE Centre: small signal gain (SSG) measurements and amplification test. Both tests were performed at two testing repletion rates: 1 Hz and 10 Hz.

During SSG measurements input energy to the 10 J amplifier stage of Bivoj system and output energy after one pass through four laser slabs were measured. The test was realized under two various cryogenic temperatures: 120 K and 150 K. The input pulses had energy of 5 mJ and were 10 ns long with exponential rise. Pump pulses had duration of 1 ms with central wavelength 939.5 nm and energy 28 J. During measurements the delay between pump and seed pulses was varied, so the amplifier was still under maximal load. This delay correlates with the effective pump energy that is seen by the input pulses.

Amplification tests were realized with seed pulses of 30 mJ with duration of 10 ns and exponential rise. The pump pulse had duration of 600 μs and maximum intensity. It was possible to optimize the transmitted wavefront to the peak-to-valley value < 0.8 λ and RMS<0.1 λ for all sets of laser slabs.

The factors of maximal amplification under various conditions during SSG and amplification tests are overviewed in Table 1.

Table 1. Overview of factors of amplification under various test conditions for four sets of Yb:YAG laser slabs. CER- co-sintered Cr:YAG-Yb:YAG ceramic disks from Konoshima; HEX – Yb:YAG monocrystalline disks with Cr:YAG hexagonal cladding; STR – Yb:YAG monocrystalline disks with microstructures in the circumference area; PLAIN – plain monocrystalline Yb:YAG disks.

	Konoshima	Crytur		
	CER	HEX	STR	PLAIN
SSG 120 K 1Hz	6,0	5,8	2,1	1,8
SSG 120 K 10Hz	4,8	4,5	2,3	1,7
SSG 150 K 1Hz	4,3	4,2	2,4	2,1
SSG 150 K 10Hz	3,6	3,5	2,5	2,2
Amplification 150 K 1 Hz	6,1	6,4	1,1	0,7
Amplification 150 K 10 Hz	4,1	3,8	1,2	0,7

From the results it is apparent that the way, how the ASE is eliminated, is crucial. The ASE suppression realized by absorber from Cr:YAG is much more effective than in the case of slabs with outcoupling microstructure patterns and as consequence the reached amplification factors are much higher. The co-sintered ceramic disks and monocrystalline disks with hexagonal Cr:YAG cladding showed very similar results. The ceramic slabs benefit from circular cladding geometry in 10 Hz regime according to preliminary results of thermo-optical calculations. Results are expected to be the same, if same geometries are used.

5. CONCLUSION

We demonstrated that Yb:YAG laser slabs prepared from monocrystals grown by Crystal Improved Growth method represent an excellent performing alternative to ceramic laser slabs for high power DPSSL systems. The geometry and the ASE suppression have the substantial impact on the achievable output power.

6. ACKNOWLEDGEMENTS

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