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Ti:sapphire crystal used in ultrafast lasers and amplifiers

Jun Dong*, Peizhen Deng

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, People's Republic of China

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Abstract

The improvement of peak power of femeto-laser depends on the compression of pulse width. The titanium-doped sapphire crystal is the excellent laser crystal with the shortest pulse width. Its theoretical pulse width limit is 3 fs. At present 50-TW tabletop Ti:sapphire lasers have been commercialized. In this paper, comparison of Ti:sapphire crystals grown by temperature gradient technology (TGT) and heat exchange method (HEM) is presented, and results show that the laser quality of Ti:sapphire crystals grown by TGT is similar to or higher than those grown by HEM. ∅ 10–30 mm high optical homogeneity Ti:sapphire amplifiers were fabricated successfully and 5–40 TW high power were obtained. We believe that up to ∅ 100 Ti:sapphire amplifiers (grown by TGT) can be obtained for ultrahigh power laser systems using all Ti:sapphire crystals in near future.

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1. Introduction

Chirped-pulse amplification (CPA) of Ti:sapphire laser crystals has created a revolution in the production of TW class lasers. The main applications of ultrashort pulse (tens fs) and high power (tens TW) lasers are ultrafast coherent X-ray generation, X-ray lasers, laser based particle acceleration and ultrafast ignition of laser fusion. To obtain higher power and high focus intensity in high power lasers, Ti:sapphire crystal and Nd-doped glass are commonly used as hybrid gain medium. Extremely high peak intensities have been achieved in both of these systems. Nd:glass produces longer, more energetic pulses than Ti:sapphire because its saturation fluence is approximately five times larger [1] ($\sim 5\,\mathrm{J/cm^2}$ for Nd:glass compared with $\sim 1\,\mathrm{J/cm^2}$ for Ti:sapphire crystal). But its gain bandwidth will support only pulses that are more than an order of magnitude longer in duration (several hundred femtosecond, compared with ~20 fs for Ti:sapphire). So the whole laser system is very large. The petawatt laser has been achieved in 1999 [2], a hybrid

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*Corresponding author. School of Optics and Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816, USA. Tel.: +1-407-823-5009; fax: +1-407-823-6880.

E-mail address: jundong@mail.ucf.edu (J. Dong).

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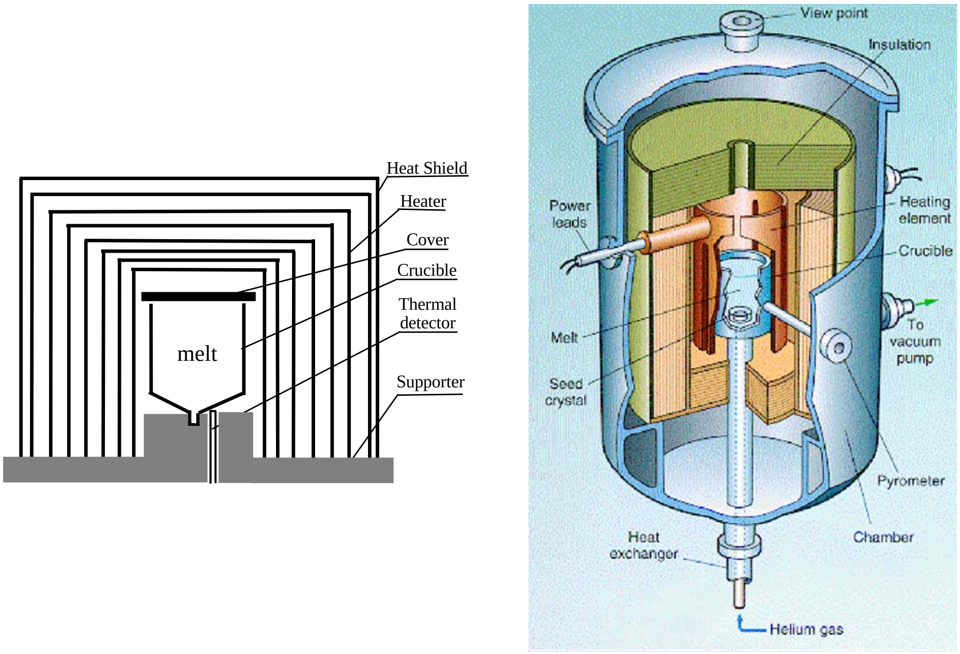
Ti:sapphire—Nd:glass laser system produced more than 1500 TW (1.5 PW) of peak power. The Brewster-cut 0.15 at% Ti:sapphire crystals were used as regenerative amplifiers, and the final focus intensity is greater than $7\times10^{20}\,\mathrm{W/cm^2}$, the highest focusing intensity achieved to date. But the laser system is still too large.

At present the high-power laser systems based on the Ti:sapphire crystals used for gain medium and amplifiers have made progress. K. Yamakawa et al. [3] described a Ti:sapphire amplifier system that has produced 100 TW laser of less than 19 fs pulse duration at a 10 Hz repetition rate with an average power of 19 W and a final amplifier efficiency reaching the theoretical quantum limit. The amplifier used a water cooled, 40 mm diameter, 25 mm length Ti:sapphire crystal with antireflection coating on both faces and is pumped with a custom-built Nd:YAG laser that is capable of producing ~7 J of 532 nm radiation at a 10 Hz repetition rate. Wang et al. [4] reported a compact tabletop Ti:sapphire laser system capable of generating >40 TW peak power pulses, with 24-fs pulse duration, corresponding to an energy of 1 J per pulse at a repetition rate of 10 Hz, and average output power of the system is 10 W. And ~50 TW all-solid-state tabletop Ti:sapphire laser systems have been commercialized. Researchers believe, if large-size and high-quality Ti:sapphire crystals are used as both gain medium and amplification medium for perawatt-class lasers, the whole laser system will be smaller and compact. In 1999, Lawrence Livermore National Laboratory (LLNL) used three large-size Ti:sapphire crystals (two ∅ 100 × 10–20 mm provided by Crystal Systems Incorporation (CSI), and one ∅ 85 × 25 mm grown by Union Carbide) as amplification media and successfully obtained perawatt-class laser output and its focus intensity was as high as $3\times10^{20}\,\mathrm{W/cm^2}$ [5]. So the growth of high-quality, high optical homogeneity and large-size Ti:sapphire crystals is the key to use all Ti:sapphire crystals as gain and amplification media for high power laser systems and make the laser system compactness.

Here we report on the research progress of growth of large-size high-quality Ti:sapphire crystals used as amplifiers in our research group and the measured optical homogeneity data of large-size high-perfection sapphire crystals grown by temperature gradient technology (TGT). Compared the Ti:sapphire amplifiers with the large-size high optical homogeneity sapphire crystals, we believe the large size Ti:sapphire crystals grown by TGT can be used as large size amplifiers for ultrahigh power laser systems.

2. The properties of Ti:sapphire crystals grown by (TGT)

Different titanium doped sapphire crystals were successfully grown by TGT [6]. The Ti:sapphire crystal boules are ∅ 110 × 80 mm, the titanium doping levels are between 0.05 and 0.52 wt%, the absorption coefficient at 490 nm is from 1 to $7.5\,\mathrm{cm^{-1}}$, the absorption coefficient can be as high as $10\,\mathrm{cm^{-1}}$ in some case (the theoretical limit is $11\,\mathrm{cm^{-1}}$ for absorption coefficient at 490 nm), and the figure of merit (FOM) of Ti:sapphire crystals grown by TGT are within 150–400. Besides the advantages mentioned above, there are other advantages that are very important factors determining the laser performance, such as low dislocation density, low scattering and high perfection of the crystal. Fig. 1 shows the crystal growth apparatus of temperature gradient technology (TGT) and heat exchange method (HEM). Although the principles for both of these growth technologies are nearly the same, the crystals are grown through the temperature gradient inside the furnace, but the formation of the temperature gradient in the furnace is totally different. The Heat Exchange Method (HEM) forms the temperature gradient through flowing helium, has allowed the growth of large sized sapphire crystal up to 32 cm diameter, weighing about 50 kg. But ⟨0001⟩ oriented sapphire crystals cannot be grown by HEM. The Temperature Gradient Technology (TGT) forms the temperature gradient field in the furnace through specially designing the heat elements, and under the static condition, any oriented high-quality sapphire crystals, especially ⟨0001⟩—and ⟨1010⟩—oriented sapphire crystal, can be grown along the seed crystal direction. The experiments showed that there is



(a)

(b)

Fig. 1. Device schematic of temperature gradient technology (TGT) and heat exchange method (HEM): (a) the apparatus of TGT, (b) the apparatus of HEM.

no manifest concentration quenching of highly doped Ti:sapphire crystals grown by TGT, and high laser efficiencies and laser damage threshold of some Ti:sapphire crystals grown by TGT are all equal to or higher than those grown by HEM in the same laser system. The concentration of titanium along the radius in Ti:sapphire crystal grown by TGT is nearly unity. Fig. 2 shows the distribution of absorption coefficient at 514 nm ($\alpha_{514\,\text{nm}}$) along the growth axis of Ti:sapphire crystal grown by HEM and Ti:sapphire crystal grown by TGT. We can see that the concentration of Ti^{3+} in Ti:sapphire crystal grown by HEM is not high, and the concentration gradient is large in the highly doped section (change from 1 cm^{-1} to 3.6 cm^{-1}). The concentration of Ti^{3+} in Ti:sapphire crystal grown by TGT is higher than that grown by HEM, and the absorption coefficient can be achieved as high as 5 cm^{-1}, and the concentration gradient is smaller than that grown by HEM (from 3 to 5 cm^{-1}). Fig. 3 shows the cw laser performance of Ti:sapphire crystals grown by TGT and HEM without water cooling at the same lasers system. Although the FOM of Ti:sapphire crystal grown by HEM is as high as 1000, 5.5 times higher than that of TGT grown Ti:sapphre crystal, but the laser performance (efficiency and output power) of HEM grown Ti:sapphire crystal is

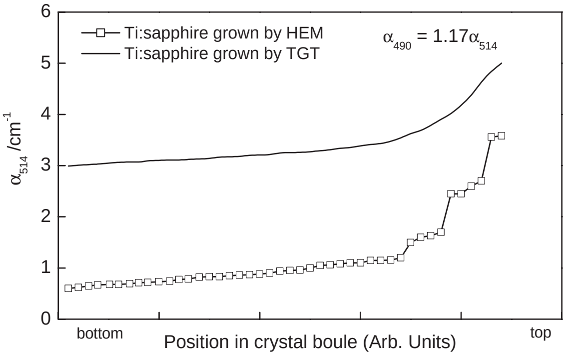


Fig. 2. The distribution of absorption coefficient at 514 nm ($\alpha_{514\,\text{nm}}$) along the growth axis of Ti:sapphire crystal grown by HEM and TGT.

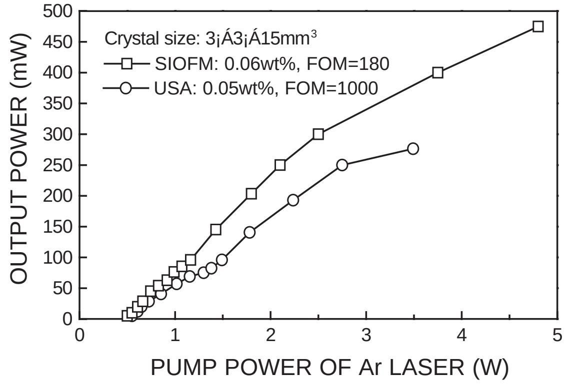


Fig. 3. The cw laser performance of Ti:sapphire crystals grown by TGT and HEM at the same laser systems without water cooling.

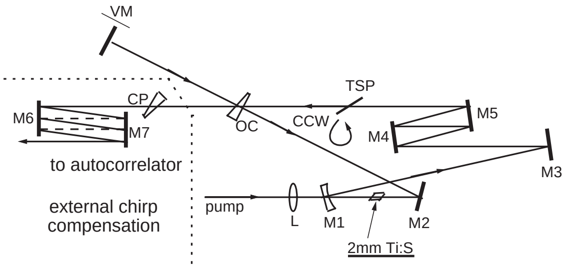


Fig. 4. Schematic of femetosecond mirror-dispersion-controlled Ti:S ring lasers, L, $f = 50$ mm lens; M1 and M2, $f = 25$ mm broadband dichroic focusing mirrors; M3–M7, dispersive mirrors; TSP, quartz plate with thickness variable from 0.2 to 1.5 mm; CP, wedged compensation plate; VM, vibrating mirror ending the slave arm; OC, 5% wedged output coupler.

obviously worse than that of TGT grown Ti:sapphire crystal. The results shows that the laser performance of Ti:sapphire depends not only on FOM, but depends more on the perfection of crystal.

Fig. 4 shows the laser experimental setup of femtosecond laser using 2 mm thickness TGT grown highly doped Ti:sapphire crystal as gain medium. The laser system was not only simplified by using highly concentration Ti:sapphire crystal with very short length as gain medium, but also highly efficient CW, mode lock and 15 fs laser output were obtained. Table 1 gives the highly efficient CW, mode-locked (ML), and femtosecond laser output data we have achieved using TGT grown highly doped Ti:sapphire crystals. So high efficiencies and ultrashort pulses can be achieved with the highly doped Ti:sapphire crystals.

Table 1
Laser performances (cw, ML and fs laser ouput of TGT grown Ti:sapphire crystals)

Laser rod (mm³)	FOM	$\alpha_{490\text{ nm}}$ (cm^{-1})	Pump power (W)	CW output (mW)	ML output (mW)	Pulse width (fs)
$5 \times 5 \times 2$	100	6.0	5	500	> 400	12[a], 8[b]
$5 \times 5 \times 5$	150	5.0	5.5	1100	750	16
$5 \times 5 \times 8$	> 150	3.0	10	> 2000	1700	16

[a] Obtained in China.
[b] Obtained in other countries.

Not only the higher laser efficiency of self-mode locked laser performance was achieved using TGT grown highly doped Ti:sapphire crystal with thickness of 2 mm, but also ultrashort pulse performance in China (12 fs) and in other counties (8 fs). To obtain such laser results, the length of lower doped Ti:sapphire crystals should be as long as 20 mm. High gain was obtained in TGT grown highly doped Ti:sapphire crystals in RIKEN, Japan in 1994, and was 100 times higher than the data reported for Ti:sapphire crystals grown by HEM at that time.

3. The progress of TGT grown Ti:sapphire crystals used as amplifiers

At present, our research group can supply the following Ti:spphire crystals as amplifiers: $10 \times 10 \times 15\,\text{mm}^3$, $15 \times 15 \times 15\,\text{mm}^3$, $\varnothing$ 18×15 mm, $\varnothing$ 20×15 mm, $\varnothing$ 30×15 mm and $\varnothing$ 30×20 mm, the largest size is $\varnothing$ 30×20 mm. First class femtosecond ultrafast pulse and tirawatt high-power laser systems have been established using TGT grown Ti:sapphire laser amplifiers in china and abroad. Fig. 5 gives two TGT grown highly doped Ti:sapphire crystal amplifiers with diameter 30 mm. 5.4 TW/46 fs Ti:sapphire laser systems have been established using these Ti:sapphire amplifiers in China. The

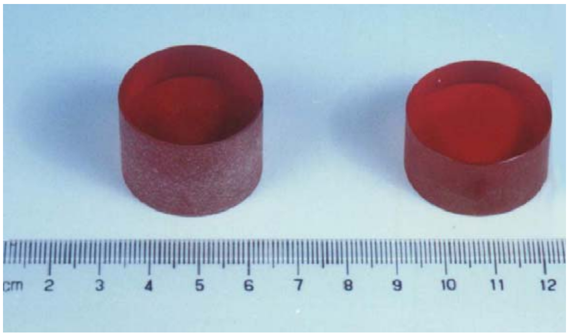


Fig. 5. TGT grown Ti:sapphire crystal amplifiers with a diameter of 30 mm.

larger size of the Ti:sapphire crystal amplifiers are required to be used in perawatt laser system. So the important thing is to grow high quality, large size and high optical homogeneity Ti:sapphire crystal. We have grown large-size sapphire crystals by TGT, and large size, high homogeneity sapphire plates were obtained from these sapphire crystal boules. Fig. 6 shows a typical display of optical homogeneity of $\varnothing$ 114×12 mm sapphire disk measured by a ZYGO Mark-III interferometer. The peak-valley (PV) value measured at 632 nm is 0.576λ, the rms deviation of the surface/wavefront map was measured as 0.100λ at 632 nm, which can be converted to an optical homogeneity (Δn) of 5×10^{-7} at 632 nm. These show that the large-size sapphire crystals have very good optical homogeneity within large area. At the same time, a typical display of optical of $\varnothing$ 30×15 mm Ti:sapphire disk was also measured by a ZYGO interferometer (Fig. 7). The peak-valley (PV) value measured at 632 nm is 0.781λ, the rms deviation of the surface/wavefront map was measured as 0.151λ at 632 nm, which can be converted to an optical homogeneity (Δn) of 9×10^{-7} at 632 nm. From the measured optical homogeneity of large size sapphire disk and Ti:sapphire disk, we believe that large-size high optical homogeneity Ti:sapphire disks can be obtained enlarging the size of Ti:sapphire crystal and improving the crystal quality. So the large-size Ti:sapphire amplifiers can be used in ultrahigh-power and ultrahigh-intensity laser system to make the laser system compact in near future.

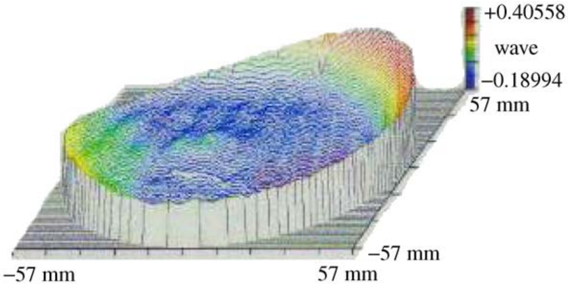


Fig. 6. Optical homogeneity of $\varnothing$ 114×12 mm sapphire disk measured by a ZYGO Mark-III interferometer, PV = 0.576λ, rms = 0.100λ, power = 0.241λ, $\Delta n = 5 \times 10^{-7}$.

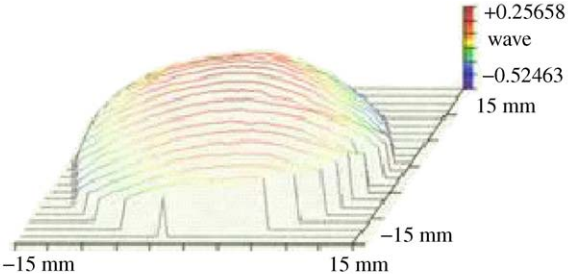


Fig. 7. Optical homogeneity of $\varnothing$ 30×15 mm Ti:sapphire disk measured by a ZYGO Mark-III interferometer, PV = 0.781λ, rms = 0.151λ, power = -0.488λ, $\Delta n = 9 \times 10^{-7}$.

4. Conclusions

High-quality and highly doped Ti:sapphire crystals were grown successfully by Temperature Gradient Technology (TGT). Femtosecond and terawatt class laser output has been achieved using TGT grown Ti:sapphire crystals in China and abroad. Based on the successful experience of high-quality, large-size $\varnothing$ 114 mm sapphire crystals, through hard work and further investigation, we believe that high-quality, high optical homogeneity Ti:sapphire disks with diameter greater than 100 mm can be obtained using TGT technology. So the ultrahigh-power laser systems can be compactness using Ti:sapphire crystal as gain medium and amplifiers in near future.

Acknowledgements

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