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LLNL-CONF-401976

Removal of Lattice Imperfections that Impact the Optical Quality of Ti:Sapphire using Advanced Magnetorheological Finishing Techniques

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March 4, 2008

euspen International Conference
Zurich, Switzerland
May 18, 2008 through May 23, 2008

Disclaimer

Proceedings of the eu**spen** International Conference – Zurich - May 2008

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Abstract

Advanced magnetorheological finishing (MRF) techniques have been applied to Ti:sapphire crystals to compensate for sub-millimeter lattice distortions that occur during the crystal growing process. Precise optical corrections are made by imprinting topographical structure onto the crystal surfaces to cancel out the effects of the lattice distortion in the transmitted wavefront. This novel technique significantly improves the optical quality for crystals of this type and sets the stage for increasing the availability of high-quality large-aperture sapphire and Ti:sapphire optics in critical applications.

1 Introduction

Ti:sapphire has become the premier material for solid-state femtosecond high-peak power laser systems because of its wide bandwidth wavelength tuning range. With a tuneable range from 680 to 1100 nm, peaking at 800 nm, Ti:sapphire lasing crystals can easily be tuned to the required pump wavelength and provide very high pump brightness due to their good beam quality and high output power of typically several watts. Femtosecond lasers are used for precision cutting and machining of materials ranging from steel to tooth enamel to delicate heart tissue and high explosives. These ultra-short pulses are too brief to transfer heat or shock to the material being cut, which means that cutting, drilling, and machining occur with virtually no damage to surrounding material. Furthermore, these lasers can cut with high precision, making hairline cuts of less than 100 microns in thick materials along a computer-generated path. Extension to higher energies is limited by the size of the crystal lasing medium.

Yields of high-quality large-diameter crystals have been constrained by lattice distortions that may appear in the boule limiting the usable area from which high quality optics can be harvested. Lattice distortions affect the transmitted wavefront of these optics which ultimately limits the high-end power output and efficiency of the laser system, particularly when operated in multi-pass mode. To make matters even more complicated, Ti:sapphire is extremely hard (Mohs hardness of 9 with diamond being 10) which makes it extremely difficult to accurately polish using conventional methods without subsurface damage or significant wavefront error. In this presentation, we demonstrate for the first time that Magnetorheological finishing (MRF) can be used to compensate for the lattice distortions in Ti:sapphire by perturbing the transmitted wavefront. The advanced MRF techniques developed allow for precise polishing of the optical inverse of lattice distortions with magnitudes of about 70 nm in optical path difference onto one or both of the optical surfaces to produce high quality optics from otherwise unusable Ti:sapphire crystals. The techniques include interferometric, software, and machine modifications to precisely locate and polish sub-millimeter sites onto the optical surfaces that can not be polished into the optics conventionally. This work may allow extension of Ti:sapphire based systems to peak powers well beyond one petawatt.

2 Ti:sapphire crystals

Ti:sapphire crystals are grown by a heat exchanger method (HEM) where the solid-liquid interface enclosing the growth plane is submerged beneath the surface of the melt which results in uniform temperature gradients at the interface. This sets the stage for a process capable of manufacturing crystals whose quality is sufficient for use in lasing applications. [1] Crystal boule sizes of 15 cm diameter can currently be grown with this process from which 10 cm diameter high quality optics can be harvested on a routine basis (Figure 1). Advances in HEM technology may soon make it possible grow crystals up to 20 cm in diameter to harvest even larger optics for innovative new laser designs. The limiting factor for harvesting high-quality large-diameter optics from the crystals is the presence of lattice distortions and discrete inhomogeneities that occur during crystal growth. These imperfections manifest themselves as localized refractive index changes in the crystal’s interior that deteriorate its transmitted wavefront quality even though the surfaces are made extremely flat. Distortions can vary from about 0.3-5 mm in width as shown in the transmitted wavefront in Figure 2(a). This distortion is large enough to disrupt the quality of a laser beam, which can cause damage to optics downstream in a laser system, and for short pulse systems can lead to incomplete compression and poor ability to focus the laser beam. As a result, any laser optic of Ti:sapphire that has these types of lattice distortions is less desirable for applications that require superior transmission characteristics and beam quality.

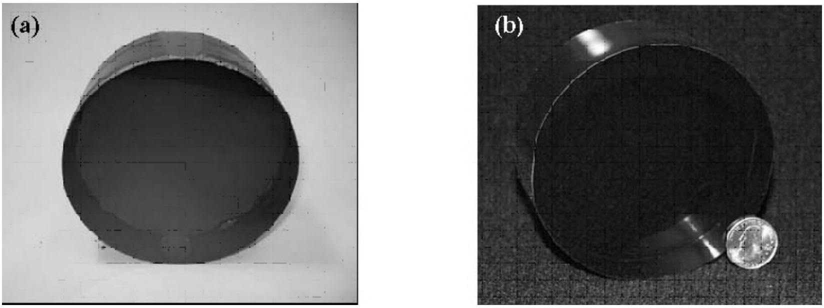

Figure 1: (a) High quality, 150 mm diameter, Ti:sapphire grown by HEM and, (b) 105 mm diameter x 46 mm thick Ti:sapphire optic.

3 Magnetorheological Finishing (MRF)

Magnetorheological finishing (MRF) imprinting techniques have been developed as a proven method for compensating for slowly-varying long-scale length (10-50 mm) lattice distortions and refractive index variations in glass and crystalline materials to provide for low transmitted wavefront distortion in plano-optics. [2] In particular, MRF has made a significant contribution in compensating for low angle grain boundaries in Yb:S-FAP [Yb3+:Sr5(PO4)3F] crystals. Currently, commercial MRF capabilities only compensate for long spatial period phase distortions of 3 mm or greater. We have developed MRF techniques to compensate for the sub-millimeter lattice distortions of sapphire and Ti:sapphire crystals to improve the transmitted wavefront. Our efforts in this area involve developing expertise and MRF equipment capabilities to correct for shorter period phase distortions and discrete inhomogeneities that can be applied in a unique manner to both glass and crystalline materials. MRF machine improvements involve novel topographical gradient fitting routines, polishing protocols, and specialized operating conditions that can deterministically correct discrete optical errors in the sub-millimeter range to improve the transmitted wavefront quality. Central to this development is the design and introduction of fiducialized MRF fixtures which accurately locate interferometric features at an absolute location in the optical plane, interferometric manipulation algorithms to relate fiducial locations to interferogram locations, enhanced fiducial camera system components that link fixtures and fiducials to within 3 μm relative to MRF machine position, and the implementation of small and precisely controlled MRF removal functions. These improvements make it is possible to achieve low transmitted wavefronts in Ti:sapphire and sapphire crystals as illustrated by comparing Figure 2a and 2b where the process resulted in marked wavefront improvement of 3.8 times in peak-to-valley and 3.7 times in rms.

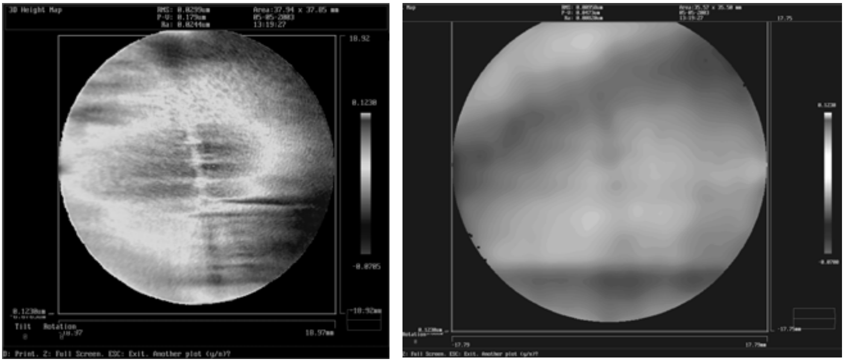

Figure 2: High quality Ti:sapphire grown HEM. Left: Transmitted wavefront of a lattice distortion that can appear in sapphire and Ti:sapphire crystals. Peak-to-valley of 179 nm, rms 29.9 nm. Right: Transmitted wavefront after MRF shows a 3.8x improvement in Peak-to-valley (47.3 nm) and 3.7x improvement in rms (8.0 nm).

3 Summary

We have demonstrated the viability of using advanced MRF techniques to compensate for discrete short-range lattice distortions that can appear in sapphire and Ti:sapphire crystals as they are scaled to larger diameters. With this technology, low transmitted wavefront distortion can be achieved from otherwise undesirable material for short pulse laser operation. Compensation of any potential lattice distortions in both sapphire and Titanium-doped sapphire will increase the availability of larger high-precision optics for many stringent optical and laser applications.

References:

[1] W. R. Rapoport, C. P. Kattak, “Titanium sapphire laser characteristics,” Appl. Opt. 27(13) 2677-2684 (1988). Also, a direct quote from the Crystal Systems website on Ti:sapphire.

[2] K. I. Schaffers, J. A. Menapace, et.al., “Growth of large laser crystals for high power lasers,” Third International Workshop on Crystal Growth Technology, Beatenberg, Switzerland, (Sept. 2005).

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.