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Frequency Converter Design and Manufacturing Considerations for the National Ignition Facility*

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Abstract

The National Ignition Facility (NIF), being constructed at Lawrence Livermore National Laboratory (LLNL), comprises 192 laser beams, Figure 1. The lasing medium is neodymium in phosphate glass with a fundamental frequency (1ω) of 1.053 μm. Sum frequency generation in a pair of conversion crystals (KDP/KD*P) produces 1.8 MJ of the third harmonic light (3ω or λ=0.35 μm).

On NIF the frequency conversion crystals are part of the Final Optics Assembly (FOA), whose two principal functions are to convert the laser light to 3ω and focus it on target. In addition, the FOA provides a vacuum window to the target chamber, smoothes the on-target irradiance profile, moves the unconverted light away from the target, and provides signals for alignment and diagnostics. The FOA has four Integrated Optics Modules (IOM), Figure 4, each of which contains two 41 cm square crystals are mounted with the full edge support to micro radian angular and micron flatness tolerances.

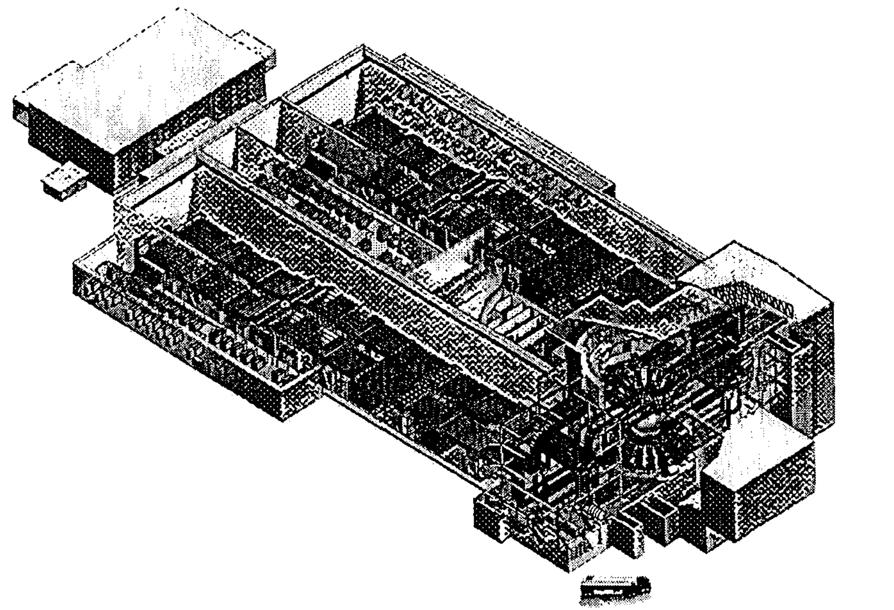

Figure 1 The NIF laser building, the 192 beamlines converge at the target chamber into 48 final optics assemblies shown in Figure 4 each one contains four final optics cells with the crystals and the focusing lens

This paper is intended to be an overview of the important factors that affect frequency conversion on NIF. Chief among these are angular errors arising from crystal growth, finishing, and mounting. The general nature of these errors and how they affect frequency conversion, and finally the importance of a frequency conversion metrology tool in assessing converter performance before opto-mechanical assemblies are installed on NIF will be discussed.

Introduction

Optical harmonic generation has long been used as an effective means for extending the operating wavelength range of high peak power lasers. Efficient transfer of power from the input beam to the generated harmonic beam is accomplished only if the phases of the input and output waves are well controlled. This is known as phase-matching and is accomplished on NIF by using the birefringence of nonlinear optical crystals (KDP and KD*P) to cancel the effects of dispersion. The phase-matching scheme on NIF is type I second harmonic generation followed by type II sum-frequency-mixing of the residual fundamental and the second harmonic light. This design is very sensitive to angular variations in beam propagation and in the crystal axes orientation.

The frequency converter on NIF must operate at a peak efficiency of 85%. Thus, it is important to control sources of angular error to a fairly high degree. For example, an angular error of 40 μrad (measured inside the crystal) leads to a 5.8% decrease in efficiency from the theoretical maximum. Angular errors arise from many sources: crystal alignment, index inhomogeneity of the crystals, surface figure distortions, mounting induced stress, gravity sag, and temperature variations. This paper will focus on how crystal growth and finishing surfaces influence frequency conversion. The mounting and metrology are briefly covered in this paper and are subject to two separate papers [Hibbard, R. L., et. al., 1998, Summers, M. D., et. al., 1998]

Crystal growth affects on frequency conversion

The baseline process for producing the converter crystals for NIF differs considerably from the method used for all previous fusion lasers. This new technique, [Zaitseva, N. P., et. al. 1991] which is referred to as "rapid-growth", utilizes highly supersaturated solutions to achieve growth rates of ten to fifty times those obtained with the conventional methods. Development of the rapid-growth method for production of large aperture crystals has reduced the growth period from about two years to six weeks, [Zaitseva, N.P., et. al. 1997]

Efficient frequency conversion requires crystals with a high degree of internal perfection. In particular, imperfections that generate spatial variations in the refractive index tensor have the potential to degrade the overall conversion efficiency. There are two primary sources of these variations: inhomogeneities in crystal composition due to differential incorporation of impurities during growth and structural defects such as dislocations and foreign inclusions. Refractive index variations are produced either directly by the compositional variations, or indirectly through the stress-optic effect by internal strains associated with both the compositional variations and the structural defects. Dislocations are the primary imperfections in conventional crystals, but due to nature of the rapid-growth process, variations in composition are the most significant sources of optical inhomogeneity in rapidly-grown crystals.

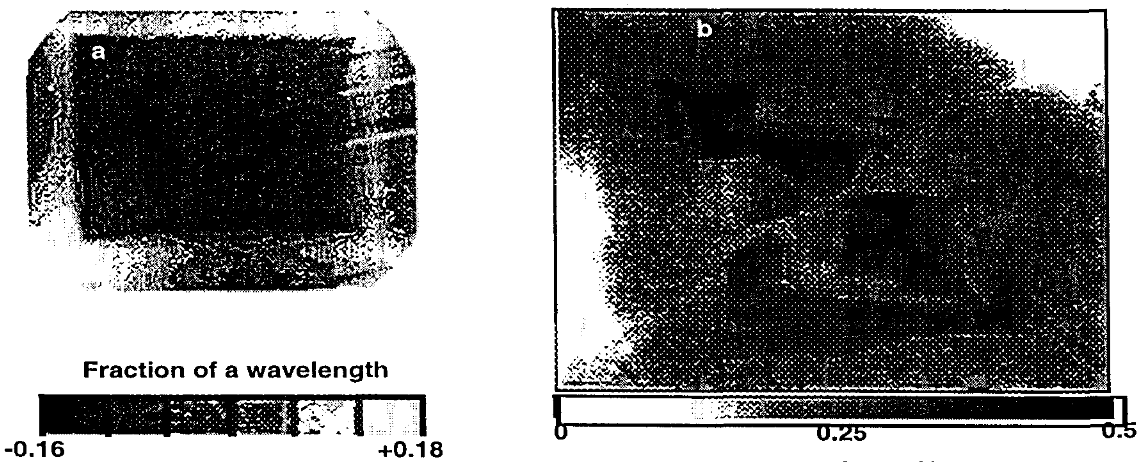

Figure 2: Transmitted wave front profiles from (001) plates of KDP with dimensions (a) 8.8x7 6x1.0cm^3, (b) 8 5x7 5x1cm^3, and (c) 41x41x1cm^3 [Symbols are: S - crystal sector boundaries, V - vicinal boundaries, and I - intervicinal boundaries.]

Figure 2 illustrates the potential deleterious effects on index homogeneity when impurity levels are not maintained at a sufficiently low level. Figure 2a shows the transmitted wavefront distortion generated by an 8.8x7.6cm KDP crystal cut from the central portion of a boule grown at 5 mm/day along the <001> axis. The difference in impurity between the {101} and the {100} sectors leads to pronounced contrast in optic index at the sector boundaries. We have demonstrated the ability to grow KDP and DKDP crystals using both conventional and rapid growth methods which meet all of the current NIF transmitted wavefront requirements as currently defined (see Fig. 2b). However the degree to which the observed inhomogeneities affect frequency conversion is not fully understood at this time. Consequently, in order to keep their impact to a minimum, higher purity KDP starting salts are being developed. Physics modeling coupled with continued metrology will also help explain the connection between inhomogeneities and frequency conversion.

Crystal finishing factors

The KDP crystal finishing process consists of all of the manufacturing steps that produce a crystal plate ready for coating from an as-grown boule of KDP. Because the exact process contains vendor proprietary information, a detailed discussion is not presented here. Instead, an overview of the process, depicted in Figure 3, is described, followed by a few comments on the diamond flycutting machine used to produce the final surfaces

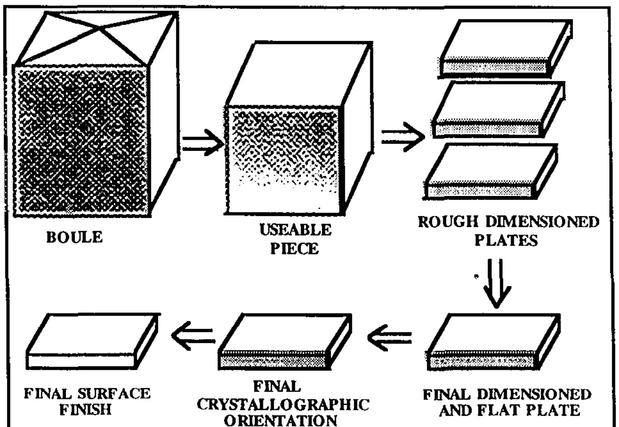

Figure 3 Overview of the KDP finishing process

An as-grown boule of KDP is inspected for detectable material flaws and internal strain. The material is mapped out and usable pieces are cut from the boule. Since Pockel cells (PC), second harmonic generators (SHG), and third harmonic generators (THG) all have different orientations between their surface normal and the material crystallographic axis, the usable pieces removed from a boule are oriented so that the maximum number of finished plates of the type intended can be obtained. From the usable pieces, plates having the rough dimensions of a finished plate are produced. Each of these is then further machined to produce a part having the final profile and geometry of a finished plate. The most critical aspect of that geometry is the free-state surface flatness of the two large faces of the plate. This flatness needs to be within 1.5 microns over the 410 mm x 410 mm area in order to facilitate orienting the crystallographic axis to the final surfaces within the tolerance required to achieve the conversion efficiency for the SHG and THG crystals. Presently a crystal orienting measurement system is used to measure the orientation of the crystal axis to the surface normal at two points, and an angle correction is computed for the next step in the process. NIF specifications will require this measurement to be done at an average angle over the entire crystal. The two large surfaces of the plate are then re-machined to create the proper orientation between the crystal axis and the surfaces, while still meeting the free-state flatness requirement. The final step is to achieve a 3 nm rms surface finish on the two faces by skim cutting them with a diamond flycutting machine. The diamond flycutting process, also effects the mid-spatial frequencies of the finished surface. This step is done in such a way that the free-state flatness of the crystal is not significantly altered.

Single-point diamond-flycutting is used because the laser damage threshold level of a diamond-turned KDP surface is significantly higher than that of the bulk material and of surfaces produced by loose abrasive polishing. Because NIF is designed to run at a laser fluence approaching the damage threshold of the bulk material, diamond flycutting must be used.[1] The performance requirements of the diamond flycutting machine needed to finish NIF crystals exceed the capabilities of commercially available machines during the initial facilitization efforts for NIF. Thus, a custom machine (planned to be complete in mid-1998,) was designed and fabricated. Follow-on technological outcome of the KDP finishing effort for NIF is an extension of the state-of-the-art for diamond flycutting machines used for the planerization of diamond-turnable surfaces.

Final optics cell design

A key design challenge for NIF has been the optical mount for the frequency converter. It is challenging because the orientations of the IOM's on the target chamber with respect to gravity are such that full edge support of the optics is required. This led to an optimized precision monolithic cell mount that houses two 41 cm square KDP crystals and a 43 cm square focusing lens to micro-radian angular and micro-meter flatness tolerances. Figure 4 shows an IOM containing the Final Optical Cell (FOC). Issues with the mount design include: maintain the surface figure of the 3 μm flat crystals, minimized stresses from the mount, avoid damage to the crystals, provide inspection methods for the crystal as mounted, and improve manufacturability. The critical design interface is the line load forcing the top side of the crystal down onto the mount. This line load has to be sufficient to hold the crystal in place, but not deform the surface figure or induce any stress into the crystal because both of these factor will adversely affect the frequency conversion efficiency. Currently interferometry, frequency conversion models and finite element analysis are being used to understand the magnitude of induced stresses and angular variations in the surface figure and their effect on frequency conversion efficiency. Stress effects on the order of 5-20 psi and angular variations on the order of 1-15 μrad are significant in terms of system performance.

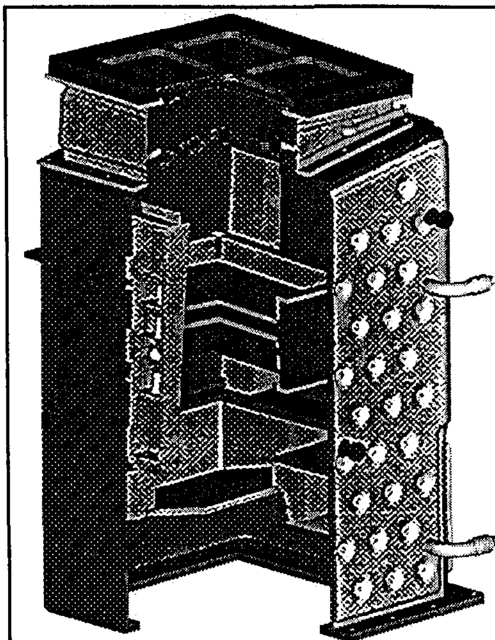

Figure 4 Shows an Integrated Optics Module which contains the Final Optics Cell and is connected by the actuation system The entire unit is in vacuum and a class 100 clean environment

Performance versus cost is a design trade-off that had to be made in the design due to the need for 192 cells The monolithic FOC cell design has many advantages in its simplicity and how it passively builds in all the desired accuracy for mounting the optics. Manufacturability has been proven at a level of 3-5 μm of surface figure. Further work is needed to finalized the specifications on the required flatness and performance of the mount. A detailed discussion of the FOC design is presented in [Hibbard, R. L. et. al., 1998].

[1] Roughness concerns spatial wavelengths shorter than 0.12 mm, and "figure" concerns spatial wavelengths greater than 33 mm.

Metrology of crystals

A device has been developed to measure the frequency conversion performance of large aperture potassium dihydrogen phosphate (KDP) crystals. The CAVE (Crystal Alignment Verification Equipment) instrument scans the crystals in a thermally and mechanically controlled environment to determine the local peak tuning angles. The CAVE can then estimate the optimum tuning angle and conversion efficiency over the entire aperture. Coupled with other metrology techniques, the CAVE will help determine which crystal life-cycle components most affect harmonic conversion. Evidence from current experiments at LLNL indicate that these curves, known as rocking curves, can shift for different spatial locations on a crystal. Significant spatial non-uniformity in frequency conversion has been observed with the 37 cm aperture Beamlet experiment. A device is needed to measure these conversion variations directly over an entire crystal.

The CAVE device is made to interrogate crystals up to the 41 cm square (NIF size). A cell has been designed to hold both a doubling and tripling crystal or a single crystal. In order to minimize distortion of the crystal from mounting, both mounting surfaces are diamond flycut to 1 micron flat. The cell flanges give an even preload of 1 lb./in to hold the crystal edges against the mounting surface. Crystals are held in a vertical position to eliminate gravity sag as they are scanned. Three actuators to tip, tilt and focus the crystal kinematically attach to the cell and are capable of tuning the angles to less than 1 m radian. A Nd:Ylf probe laser and regenerative amplifier that can achieve an irradiance 4 GW/cm^2 upon entering the crystal is used. The system is housed in a positive pressure clean room enclosure to maintain temperature, acoustic and particulate control.

The first CAVE prototype is currently being constructed and tested at LLNL. The device scans KDP crystals and measures conversion efficiency vs. rocking angle for any spatial location. The CAVE is designed for accuracy of 10 m radians in phase matching angle measurement and 1% in conversion power measurement. The machine errors will be tested and analyzed to lead to a final design that will be used for final verification of the NIF frequency converters. The immediate use for the CAVE device will be to help advance crystal development to reach the NIF conversion goals. An important long term use is to verify assembled cells before they are installed into NIF. A detailed discussion of the FOC design is presented in [Hibbard, R. L., et. al., 1998].

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