Research on laser damage of final optics assembly on high power laser facility

Dongfeng ZHAO[1,2], Rong Wu [1], Zunqi LIN[1], Li Wang[1], and Jianqiang Zhu[1]

[1]Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, No.390, Qinghe Road, Jiading District, Shanghai 201800, China
[2]University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China

ABSTRACT

In order to improve laser damage resistance of the Final Optics Assembly (FOA), simulation analysis have been done for 1ω, 2ω and 3ω laser beam considering ghost images to the 4th order. The panels of ground glass scatter ghost laser around the FOA walls and the panels of architectural glass absorb the 1th order energy. The appearance of smoothing fused silica surface defect and the effect of wiping off etching contamination are researched on HF-based etching processes under ultrasonic. Now, 18 shots were executed using 310×310mm laser with 3ns pulse width. During the experiment, the third harmonic laser terminal output energy is 1500J~3500J, and the maximum laser energy flux is about 4J/cm^2. This presentation addresses the optical configuration of the FOA, the simulation analysis of ghost, the way of ground glasses absorbing energy and the result of laser damage resistance of fused silica on HF-based etching processes under ultrasonic.

Keywords: Laser Damage, Fused Silica, Final Optics Assembly, High Power Laser Facility

1. INTRODUCTION

Shenguang-II Upgrade (SG-II Up) is a kilojoule-class solid-state laser and targeting facility under construction by the National Laboratory on High Power Laser and Physics. The amplified 1053 nm beams from the Nd:glass driver are transported (at 40 kJ for 3 ns) in 2 × 2 quads with 8 beams to the 2.4 m-diameter target chamber where eight final optics assembly (FOAs) convert each beam to the third harmonic, separate the residual 1053 and 527 nm beams, and finally focus the 351 nm beam onto the target.

The design and manufacture of the FOA has been finished, and it is different from NIF'FOA, SG-II'FOA, SG-II Up' prototype FOA and SG-III'FOA[1–4]. FOA consists of fixed interfaces to the target chamber and four modules accommodating seven full-aperture optical elements, shown as Figure 1. The corresponding functions of these optical elements are also shown in the figure caption.

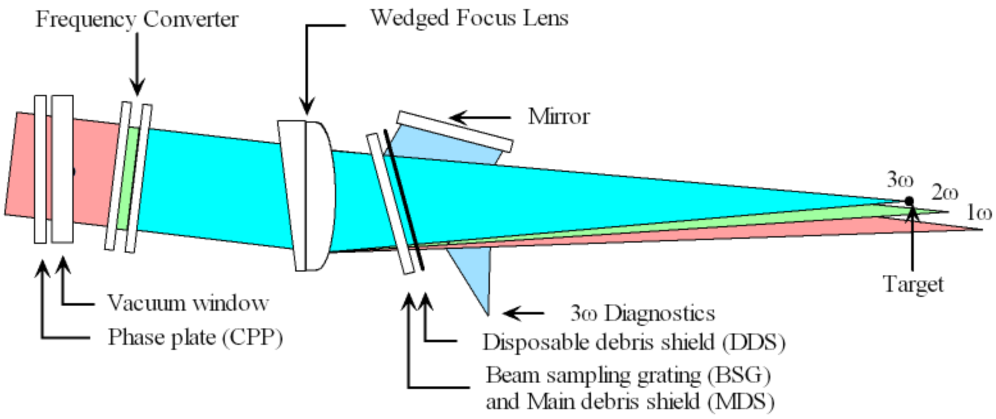

Figure 1. The FOA prototype with beam aperture of 310×310 mm.

1. Phase plate – conditions the beam phases to form an ~400 µm flat-top profile
2. Vacuum window – provides a near-vacuum FOA environment
3. Frequency conversion crystals – convert the 1053 nm beam to a 351 nm beam
4. Wedged Focus lens – focuses the 351 nm beam onto target, and separates the residual 1053 and 527 nm light

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Correspondence to: Dongfeng Zhao, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, No. 390, Qinghe Road, Jiading District, Shanghai 201800, China. Email:dfzhao@siom.ac.cn

Laser-Induced Damage in Optical Materials: 2014, edited by Gregory J. Exarhos, Vitaly E. Gruzdev,
Joseph A. Menapace, Detlev Ristau, MJ Soileau, Proc. of SPIE Vol. 9237, 92371V · © 2014
SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2066260

with 351 nm light
5. Beam sampling grating (BSG) and main debris shield (MDS) – provide a low-efficiency grating to the input surface for energy sampling (calorimeter) and large-object protection for upstream (more expensive) optics
6. Disposable debris shield (DDS) – thin, inexpensive optics for primary debris protection
7. Mirror– reflect energy sampling to calorimeter

Frequency converter is a cascade sum-frequency generation design consisting of a 12.5 mm-thick Type-I KDP doubler and a 10.5 mm-thick Type-II KDP tripler, which is optimized to achieve >70% peak power conversion efficiency to the third harmonic at a 1ω driver irradiance of 3 GW/cm^2[7]. The wedge focus lens, which is a prism with an edge angle of 11.22° to combine with the focus lens to realize a 2 mm separating distance of the fundamental and second harmonic away from the third harmonic target, has a 85 mm-thick meniscus-aspheric surface for avoiding optical damage induced by ghost images of the fourth order for 1ω, 2ω and 3ω, as well as for the back-reflected light from the target, thereby improving the focus-spot quality. BSG and MDS are made with 8 mm-thick fused silica possessing a 0.2% low-efficiency grating on the input surface for energy sampling. This setup provides transitions from the near-vacuum FOA environment to the hard-vacuum target chamber environment. The disposable debris shield is a 2 mm-thick borosilicate glass. Here, the angle of the normal direction of the BSG and MDS to the DDS and the direction of the incident beam is 13.5°, which is used to deviate ghosts below the fourth order for 1ω, 2ω and 3ω from the direction of the incident beam. Inside the FOA, the pressure is 10 Torr with 10 SLPM before the laser shot and 50 Torr with 40 SLPM after the laser shot to purge using clean dry nitrogen.

2. EVADING GHOST IMAGES

The optics in the FOA are coated with a sol–gel anti-reflection film, but residuary (0.5%–1%) reflection also exists. Hence, these 7 optics (including 14 surfaces) could form thousands of ghost images within the fourth-order reflection. If these ghost images are located on the optical elements, they would be directly damaged; if the ghost images move to other parts such as the mechanism, wire, and silica gel, the optics would be indirectly damaged because of the contaminants. As shown in the last section, the BSG, MDS, and DDS are tilted by 10°, and most of the ghost images are deflected from the main beam path to protect the optics. These ghost images lead to another problem, i.e., the presence of contaminants. In this section, the numerical simulation is carried out based on the FOA construction and the way of ground glasses absorbing energy are presented.

2.1 Simulation analysis

Here, we use the optical design and analysis software ASAP to model and analyze the stray light with the following conditions and parameters: (1) 1ω flux is 6.7J, harmonic conversion efficiency is about 60%, and 3ω flux is 4J/cm^2@3ns. (2) The envelope of near field is super-Gaussian. (3) Considering the degeneration of Chemical anti-reflection film during the experiment process, the single reflectivity is set to 1%. (4) The maximum order of ghost image is 4th. (5) The focal length is 2234mm with ±15mm stroke of axial translation. The final analysis result is shown in Figure 2. There are 3 tips should be noted: (1) red denotes 1ω and blue denotes 3ω, (2) the shape of rectangle is for 1st, circle is for 2nd, triangle is for 3rd, and square is for 4th, (3) the safe distance to the surface of each optical element is 10mm.

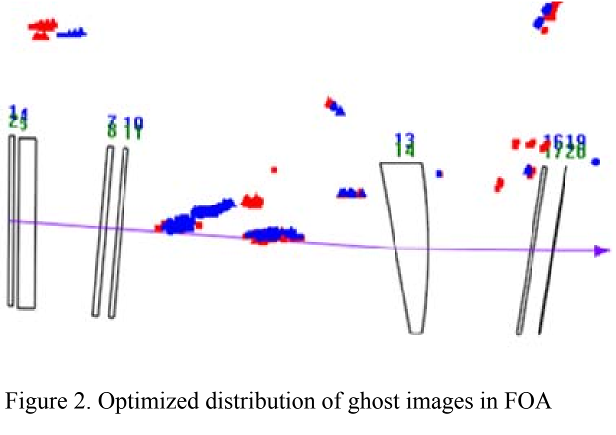

Figure 2. Optimized distribution of ghost images in FOA

The optimized design arrangement of FOA is depicted as Figure 3, including the distance of optical elements and tilted angle to optical axis.

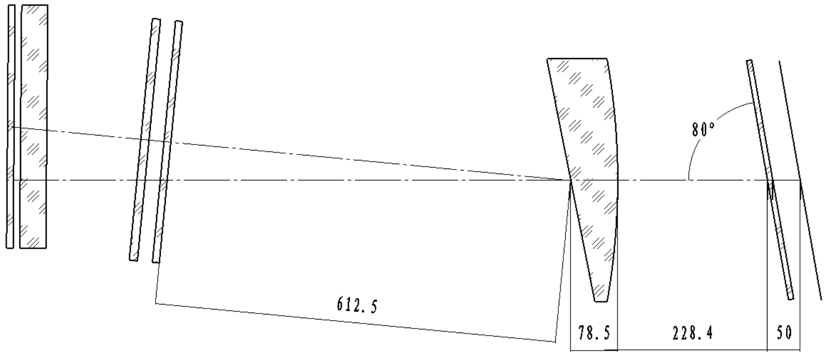

Figure 3. The optimized scheme of FOA

2.2 scattered by ground glass

To avoid the damage caused by the irradiation of ghost image, we use ground glass to scatter ghost laser and protect the machinery materials. A ground glass layer is constructed to separate the surrounding mechanical barrel, and the glass material is fused silica. Figure 4 is the scheme of the ground glass layer, with two points should be noted: (1) for 1st ghost image, we put absorption glass behind ground glass to ensure that effective absorption is done even if residual leak laser transmit through the ground glass. (2) Some sinusoidal structure is etched in the ground glass to scatter the reflected laser when grazing incidence arises.

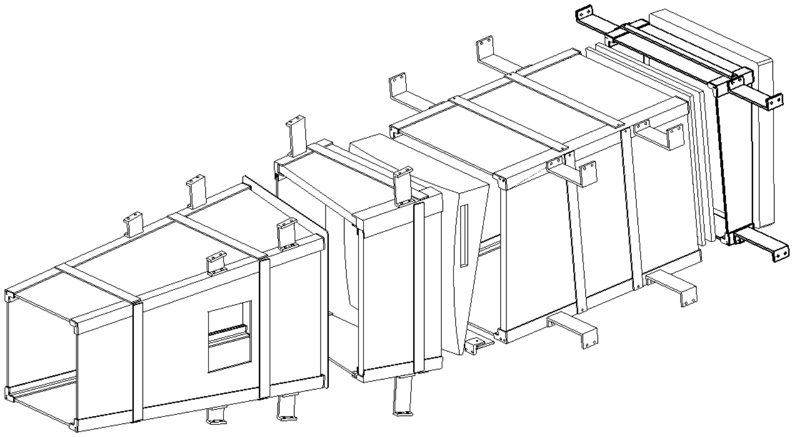

Figure 4. the shape and structure of ground glass layer in FOA

3. HF ETCHING ASSISTED WITH ULTRASONIC

The intrinsic laser damage threshold of silica bulk is about 100J/cm^2 at 351nm at nanosecond, however, after surface polishing and coating, the laser damage resistant threshold is significantly reduced. Currently, the maximum output laser flux at 3ns is only ~ 8J/cm^2 by NIF in USA, and after running some enough shots there will be varying degrees of damage in the internal and surface of fused silica components. Some damage is caused by self-focusing of laser nonlinearity, and the most important damage is because of the processing element surface defects caused by residual impurities particle. Surface defects not only reduces mechanical strength of the optical material surface, but also bring about refraction, reflection and other phenomena which will cause rapid increase of the local laser intensity due to interference. Moreover, residual impurity particles will heat up very quickly because of local explosions and cause splashing. They will both damage the fused silica surface, and in the subsequent multiple pulsed laser irradiation, the initial damage will continue to grow exponentially.

To reduce the defects and residual impurities in surface, Menapace used flexible MRF magneto-rheological technology to improve processing technology[5-6], Lamaignere used laser pretreatment [7-8] and Suratwala used HF acid etching method to smooth surface defects and remove particulate impurities[9-10]. Especially HF acid etching can effectively remove embedded impurities and particles. Various laboratories have carried out appropriate research, but found etch residues deposited secondary problem. American LLNL's AMP advanced cushioning technology [11], introducing ultrasound-assisted during HF acid etching process, can solve the problem and improve the smoothing effect. This process has been applied to all fused silica in NIF. Here is the mechanism study of pollution and passive components surface defects with introduction of ultrasonic agitation. Some experimental study will be conducted to master all kinds of parameters and effects in the HF etching process and enhance the understanding of laser induced damage of fused silica.

3.1 Mechanism of ultrasonic assisted HF acid etching

During the grinding and polishing process of fused silica glass, the surface-induced injury will occur from top to bottom is: (1)~200nm polishing heavy deposition layer, (2)~10μm sub-surface defect layer and (3)~200μm element substrate deformation layer connection. The most impact to laser-induced damage is the sub-surface layer, including pits, cracks and particles embedded in them. Cracks weaken the mechanical strength of the optical element surface, and they may raise the light intensity which makes some high-level local intensity; Furthermore, impurity particles can absorb laser energy strongly, leading to rapid warming and burst in the surface.

From theoretical analysis, we can use electric field intensification to express the impact of sub-surface defects, which can be quantified as the light intensity enhancement factor (LIEF). Bloembergen [12] discovered that maximum factor LIFE near the crack was approximately n^4 (n is the refractive index component). Genin[13] added light propagation effects to the optical field enhancement calculations, and obtained LIFE=10.2 by a business software using finite difference time domain FDTD method. The maximum LIEF would be up to 27, if we consider some adjacent defects. Therefore, controlling the sub-surface defects is key method to reduce the intensity enhancement. Now we generally use HF acid to etch and smooth the optical surface. However, once introducing defects, the top re-polishing layer deposited is firstly etched rapidly, and opening width of defect is increased forming some smoothed cosine shape structure. More simply, the presence of sub-surface scratches or cracks will not disappear in etching, but open more widely and smoothly, shown in Figure 5. This will not only improve the mechanical strength around defects, but also significantly reduce LIEF caused by defects. With the HF acid etching process, the reaction product is SiF_6^{2-} (six fluorine silicon) which cannot be easily dissolved in the solution and deposited on the surface of the optical element.

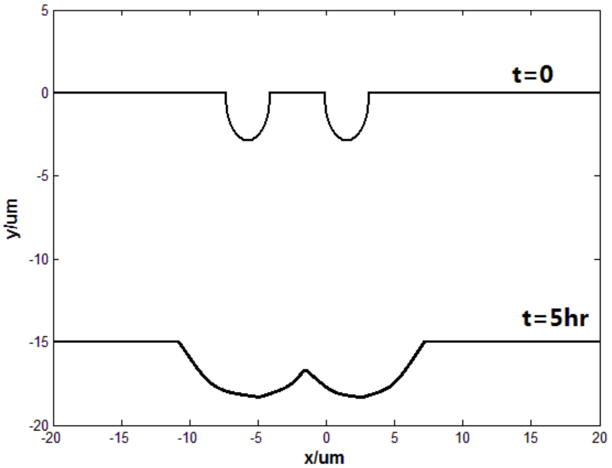

Fig.5 Schematic illustration of etching cracks on the surface of fused silica

The mechanism of ultrasonic cleaning is liquid cavitation, i.e., the ultrasonic energy transmitted by the liquid molecules, the molecular interaction of a large amount of bubbles, the energy accumulation to an extent of the collapse of bubble generation of the liquid huge energy burst. Hence, assisted with ultrasonic agitation, the chemical equilibrium constant in Eq. (1) increases and the solubility of hexafluorosilicate improved. Moreover, the shock wave energy generated by the collapse of bubble from the surface to promote rapid release particles. Ref. [9] proposed that bubble diameter d_b

determines the range and intensity around the surface. Obviously, the smaller the better, which means require much higher frequency (prefer ~MHz). Bubble diameter expression is:

$$d_b = \frac{1}{\pi f}\sqrt{\frac{3\kappa p_0}{\rho}}\,, \tag{1}$$

where f is ultrasonic frequency, p_0 is hydrostatic pressure (typically 1atm), ρ is liquid density (1gm/cm^3), and κ usually is 1.3. Another boundary sound layer thickness δ_{ac} under ultrasound determines the impurity particles are transport effects:

$$\delta_{ac} = \sqrt{\frac{\mu}{\pi f \rho}}\,, \tag{2}$$

where μ is the liquid viscosity. Clearly, the reaction product can diffuse more easily to external solution with thinner δ_{ac}. For one hundred KHz ultrasound, the thickness of the layer of about 2-5 microns, for the MHz megasonic, the thickness of the layer will be less than 0.5 microns, and can remove one hundred nanometer particles. Thus, the particles can be removed at different scales under different ultrasonic frequencies. To sum up, in the process of HF acid etching with ultrasonic agitation, bubbles rupture around the silica surface peeling particles away from the surface, meanwhile, the etching speed will be much faster than the static HF acid. The higher frequency, the faster catalytic rate (usually1-2 times). Furthermore, the optimal breadth depth ratio of smoothed defect is >4.

3.2 Experimental results

Here, HF is 2.5-10% at various ratios under different agitation conditions (static, ultrasonic or megasonic conditions at various frequencies), and the etch times is too different. A description of the detailed process parameters used for each of the samples is shown in Table 1. The sample was first submerged in a polypropylene tank filled with the acid and agitation was generated with ultrasonic transducer (1000kHz). Subsequently the samples were removed and submerged in a de-ionized wateriness tank also agitated with a multi-frequency ultrasonic transducer (68 and 132kHz). Finally, the samples were sprayed by de-ionized water and dried by nitrogen. During the etching and rinsing processes, the samples were mounted in Teflon frames held only on the edges of the sample. The size of ground and polished fused silica samples is 50×50×10mm, and the silica type is Corning 7980.

Table 1. Experimental parameters

Sample	Fused silica optics							Fused silica grating	
	1	2	3	4	5	6	7	8	9
Comp/Conc	NA	1:10	1:10	1:9	1:9	1:8	1:8	NA	1:37
Ultrasonic Agitation Time(min)	NA	2	5	10	15	20	20	NA	5
Etch Time(min)	NA	6.5	40	120	200	330	825	NA	5

Test laser wavelength is 355nm with 6ns pulse width, and the spot size is 0.62mm^2. The test method is 1-on-1 way, and the shot points are 15 in each energy level. The test results of laser damage resistant threshold were shown in Table 2. According to the test result, with ultrasonic assistance, the resistant threshold was improved 70.6% after etching about 25μm. Additionally, the threshold of grating also increased about 20% after 65nm removed.

Table 2 Summary of etching depth and laser damage test results of samples

sample	Fused silica optics							Fused silica grating	
	1	2	3	4	5	6	7	8	9
Etching depth (μm)	0	0.16	1.0	3.2	5.4	10	25	0	0.07
Laser damage threshold(J/cm^2@355nm)	5.1	6.5	6.8	7.2	7.5	8.2	8.7	3.5	4.2

4. DAMAGE EXPERIMENT OF FOA

Total 18 shots were executed using 310×310mm laser with 3ns pulse width. During the experiment, the third harmonic laser terminal output energy is 1500J~3500J, and the maximum laser energy flux is about 4J/cm^2. The specific energy results are shown in Figure 6. Component damage does not appear until 4500J at 1ω, only a certain number of two crystals causing chemical film halo-like dust and dirt from the gray point. At eleventh shot, Wedged Focus Lens's aspheric surface appear the first 100μm damaged point. Next, 1 or 2 new points appear following the shot. And at the end of experiment, the surface are total 12 damage points about 300μm. But the plane surface doesn't appear damage. After analysis, the reasons of damage are 3 ω near-field modulation, contaminations on the optical surface and excessive B-integral.

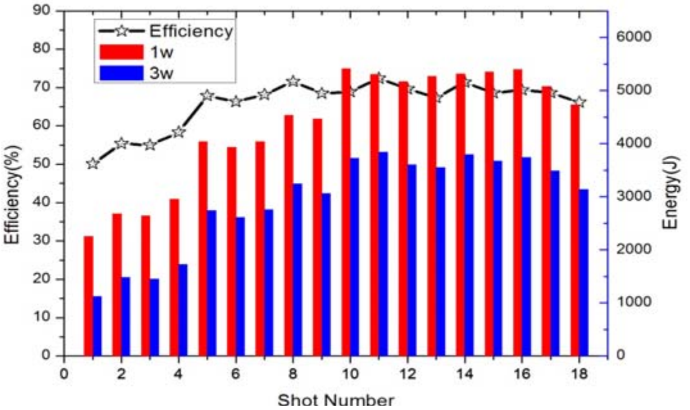

Figure 6. Experimental parameters of 1 ω and 3 ω energy and third harmonic conversion efficiency

5. CONCLUSIONS

In summary, we have completed the optimal design of FOA based on the 4th ghost image and HF acid etching method with ultrasonic and megasonic assistance. A series of high energy shots show that FOA can run in the flux of 4J/cm^2@3ω. And the laser damage of FOA is induced by three causes about 3 ω near-field modulation, Φ 100μm contaminations on the optical surface and the thick about 80mm of Wedged Focus Lens.

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