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Fabrication and Applications of Large Aperture Diffractive Optics

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Fabrication and Applications of Large Aperture Diffractive Optics

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Abstract

Large aperture diffractive optics are needed in high power laser applications to protect against laser damage during operation and in space applications to increase the light gathering power and consequently the signal to noise. We describe the facilities we have built for fabricating meter scale diffractive optics and discuss several examples of these.

Keywords: Diffraction gratings, Fresnel lenses, Computer generated holograms, large aperture diffractive optics, kinoforms, high power lasers, space telescopes

Introduction

In recent years, diffractive optics are finding an increasing number of applications. While diffraction gratings have been extensively used in spectrometers for many years, spot array generators in optics interconnects, fiber Bragg gratings, laser beams shapers, and computer generated holograms are examples of more recent diffractive optics applications. A majority of these applications, especially the more recent commercial ones, require diffractive optics at small aperture sizes (in the mm to a few cm size). Large aperture diffractive optics, on the other hand, find applications in high power lasers and in space optics.

In high power lasers, large aperture optics are required in order to minimize the optical damage to the optic. The area of the optic is often set by the laser damage threshold fluence and the maximum amount of the laser energy incident on the optic. For example, in the Nova laser system at the Lawrence Livermore Laboratory (presently non-operational), the largest optic had to be approximately 70 cm in diameter in order to propagate ~ 4 kJ of laser energy in a 3 ns pulse at 351 nm. The estimated laser damage fluence at this pulse length was about 2-4 J/cm2. In the National Ignition Facility presently under construction at our Laboratory, the laser damage fluence of the optics at 351 nm is expected to be around 15 J/cm2 for the 3 ns pulse because of the improvements in optical finishing processes. Because of this increased laser damage threshold, more laser energy can be propagated through a given optical aperture. Thus, nearly 11 kJ of laser energy in a 3 ns pulse at 351 nm is expected to be propagated through a 40 cm square aperture optic. The NIF laser system will have 192 laser beams which together will deliver approximately 1.5 MJ of 351 nm light to the target [1]. In the current baseline, each of the 192 beams is expected to have a shallow diffraction grating for sampling the laser beam energy and a continuous phase plate for homogenizing the focal spot. These diffractive optic are at the full 40-cm square aperture size.

Another high power application that requires large diffractive optics is the Petawatt laser. Here the chirped pulse amplification (CPA) concept is used to generate ultra high peak powers. In CPA, a short, low energy pulse is 'stretched' in time using a pair of small aperture diffraction gratings. This stretched pulse is amplified through a conventional laser amplifier chain such as the Nova laser. Finally, the amplified, stretched pulse is recompressed in time using another pair of diffraction gratings. The gratings in the compression stage have to be at large apertures in order to be able to withstand the high fluences. The Petawat demonstration at the Lawrence Livermore Laboratory [2] used 94-cm diameter diffraction gratings for pulse compression. These were submicron-pitch, holographically ruled plane gratings. Similar gratings are currently being employed at other Petawatt laser facilities under construction. The size of these gratings is again set principally by the amount of the laser energy generated and the laser damage fluence of the gratings.

In space applications, large aperture optics are required to increase the light gathering ability and consequently the signal to noise ratio. Examples here are the large aperture primary mirrors in space telescopes. The largest ground based telescope, the Keck telescope in Hawaii, has a 10 m diameter primary mirror comprising of 36 1.8 m wide (corner to corner) hexagonal shaped mirror segments. The largest space based telescope, the Hubble has a monolithic primary mirror of 2.4 m diameter. The resolution as well as the signal strength are directly related to the aperture size and get better with increasing apertures. In the proposed Gossammer space telescope initiative by NASA [3], the apertures are envisioned to be in the 50-100 m diameter range.

Diffractive optics fabrication facilities

Fabrication of large aperture diffractive optics poses many unique challenges. A common way of fabricating such optics is by using lithographic techniques. Here the substrate is coated with a uniform layer of photoresist which then is exposed either to an interference pattern (for fabricating diffraction gratings) or to an intensity pattern transmitted through a mask (for making kinoforms or continuous phase plates). Following the exposure, the photoresist is developed to create a surface relief pattern. At this stage, a gold overcoat can be applied to the relief pattern in resist leading to a reflective grating (for example). On the other hand, for transmissive diffractive optics, the surface relief pattern can be transferred into a glass substrate (often fused silica) by either wet-etching or by dry etching. These are fairly standard methods in diffractive optics fabrication and are widely used by the researchers in the field. The uniqueness of our work lies in the application of these techniques to large aperture (~ 1m size) diffractive optics fabrication.

In conventional lithography, the photoresist coating is applied to the substrate using a spin coater. However, this technology does not easily scale up to larger aperture sizes. There are several reasons for this. The large substrates are often heavy (especially those fabricated for reflective optic) and these can not be spun at the high speeds required for coating. If one uses a dip coating technique, a large amount of photoresist as well as a large dip tank are needed for this. The uniformity of the coating for large apertures produced by the spin coating method is also not very good. For these reasons, we have chosen to apply the photoresist coating to large aperture substrates using a meniscus coating method. A picture of our meniscus coater is shown in figure 1. In the meniscus coating method, the photoresist is pumped through a precisely machined slot and the optic to be coated is moved at a constant speed slightly above this slot. As the part moves over the flowing photoresist, a thin resist layer is deposited over the optic. The thickness of the deposited layer is proportional to the2/3 power of the velocity. The meniscus coater is used to apply photoresist and other dielctric layers to substrates up to 1 m x 2 m. For thin layers (< 1 μm) the flatness is better than λ/10 at 633 nm. We have also applied up to 30 μm thick coatings with about 5% uniformity over ~1 m size substrates.

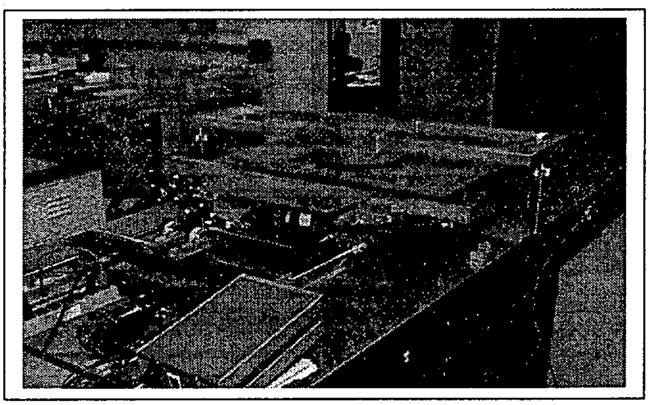


Figure 1. The meniscus coater used for depositing photoresist coatings on large aperture sustrates.

Methods of fabrication for diffraction gratings consist of ruling the grooves with a mechanical tool or an electron beam and interference lithography. Conventional ruling using a mechanical tool becomes impractical for high groove densities. The tool wear also becomes an issue for large sizes. E-beam writing, while possible for a wide range of groove densities, quickly becomes cost-prohibitive for large apertures. Interference lithography, on the other hand, is a complementary tool to these methods. In interference lithography a layer of photoresist is exposed to a sinusoidal intensity pattern produced by the interference of two coherent beams. A picture of the large aperture exposure facility is shown in figure 2. A laser beam from a Kr-ion laser is split into two sub-beams and two beams are collimated using custom fabricated 1.1 m diameter aspheric fused silica lenses. The two collimated beams interfere at an angle and the interference pattern exposes a photoresist layer deposited on over the optic. The exposure area is ~1 m diameter circle. The groove densities can be up to 2000 lines/mm with this facility. Through a careful control of the photoresist type, the exposure and development steps, groove profiles from sinusoidal to lamellar can be produced on up to 1-m wide apertures.

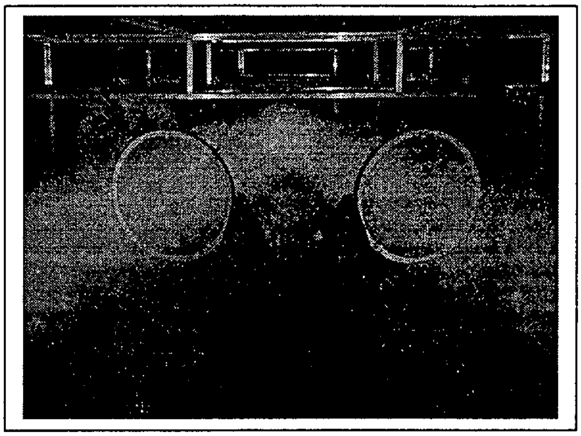
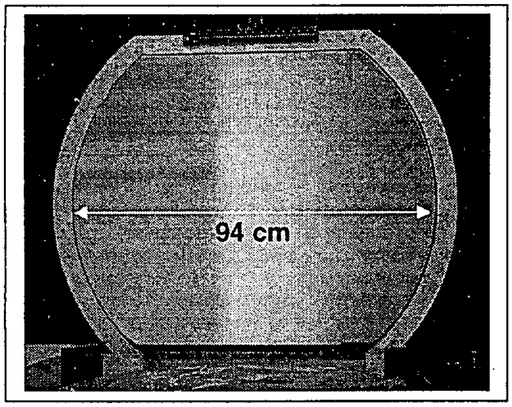


Figure 2. The large aperture interference lithography exposure station. Shown in this picture are the 80-cm fused silica lenses for collimating the 414 nm laser beams. The current set up uses 1.1 m diameter lenses.

In addition to the meniscus coater and the holographic exposure facility, we also have mask making and mask-alignment machines, baking, wet processing (for cleaning, developing, HF acid etching etc), vacuum processing (for deposition of metallic and dielectric coatings) and ion-etching facilities for handling up to 1-m size apertures. Finally, the fabrication infrastructure is complemented with a suite of the state of the art optical and diffractive optic design codes.

Examples

In this section we discuss some of the large aperture diffractive optics fabricated at our facility. Figure 3 shows a picture of a 94-cm diffraction grating for use in the pulse compression stage of a Petawatt laser. We have made several such gratings for various Petawatt laser facilities under development through out the world. The grating substrate used was a 12 cm thick BK7. We have also fabricated such gratings on fused silica substrates. The groove density was 1480 lines per mm. The grating structure was first formed in photoresist using interference lithography using two collimated beams and subsequently overcoating it with a thin gold layer. We measured the diffraction efficiency of this grating in a reflecting –1 order in a Litro configuration. A spatial map of the efficiency is shown in figure 4. We see that the grating efficiency is greater than 92% over the aperture with good uniformity. To the best of our knowledge, our facility is the only one that can fabricate gratings of such quality and aperture sizes.



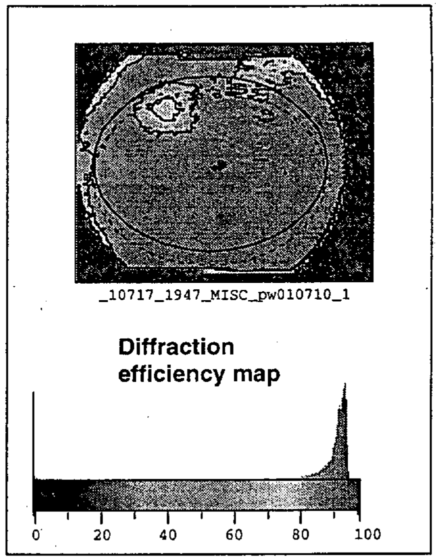
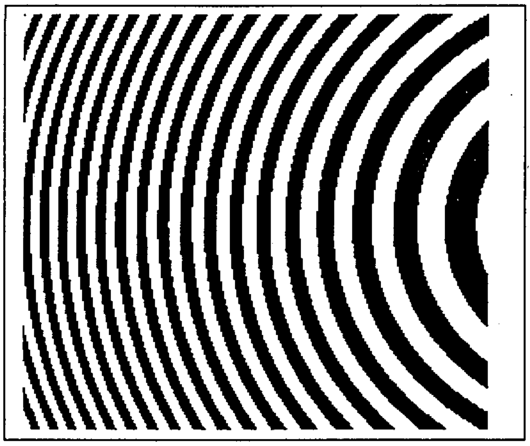


Figure 3 (above). Picture of a 94-cm diameter diffraction grating fabricated using interference lithography.

Figure 4 (right). Spatial map of the diffraction efficiency of the 94-cm grating.

Next example we present is a transmission grating in a 40 x 40 cm wide, 1-cm thick fused silica substrate fabricated using interference lithography and wet etching. This grating is a prototype of the gratings that will be used for sampling the high power beam on NIF. The requirements are that the grating diffract a small fraction (~ 0.3%) of the incident high power laser beam and bring it to focus at a distance of approximately 1.5 m from the optic. The sampled beam also needs to clear the main (zeroth order) beam. These implies the grating structure to have shallow (~20 nm deep) concentric grooves as shown schematically in figure 5. We used interference lithography with diverging beams to fabricate the grating structure in photoresist. At the end of the lithography step, the photoresist grooves were separated by clear areas. At this stage we transferred the grating pattern into the fused silica substrate by etching clear areas using a buffered hydrofluoric acid solution. Finally the remaining resist as washed off leaving a clear fused silica optic with ~20 nm deep grating profile. Figure 6 illustrates the operation of such a beam sampling grating. Here the grating is illuminated with a whitelight source (hidden behind the screen)and the converging and the diverging diffracted orders are seen on the screen past the grating. In the coming years we will be producing several such gratings for the NIF laser beams.

Final example we will discuss here is the development of Fresnel lenses for space telescopes. Other examples such as ion etched fused silica gratings, dielectric multiplayer gratings and kinoform phase plates will not be discussed here because of space limitations. Recently we have proposed a large aperture diffractive telescope concept for imaging of exo-solar planets [4]. Such telescopes consist of a large aperture (25-100 m diameter), long f-number (50-100) transmissive Fresnel lens primary and a much smaller secondary system which is physically separated from the primary but is optically



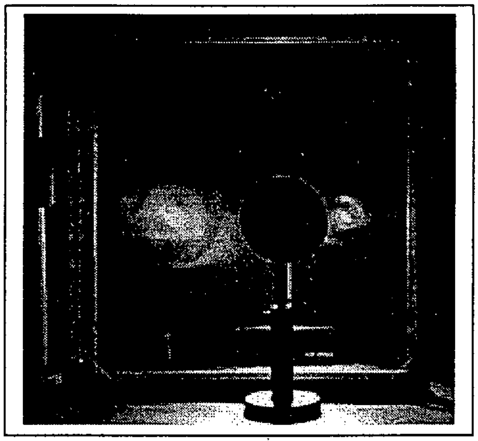


Figure 5. Schematic of the beam sampling grating groove profile

Figure 6. A 40-cm aperture beam sampling grating in operation. A white light source located behind the black circle in the center of the picture illuminates the grating. The converging and the diverging diffracted orders are seen at the screen located behind the optic.

connected to it. Long f-number lenses offer significant advantages over the mirrors by being less sensitive to surface deformities during their operation. Space deployment of such systems requires that the lens be light weight and hence a Fresnel lens. The chromatic effects inherent to a diffractive Fresnel lens can be completely compensated for in the secondary part of the telescope by using a correcting secondary Fresnel lens. We have recently demonstrated the broad-band (470-700 nm), near diffration limited operation of such a telescope in the Laboratory using monolithic Fresnel lenses fabricated in 1-cm thick monolithic fused silica substrates [5]. Figure 7 illustrates a binary mask produced for fabricating a 50-cm diameter f/100 Fresnel lens. The lens was fabricated in 1-cm thick fused silica substrates using a 2-mask lithography process and wet etching.

Scale up of such Fresnel lenses to space telescope applications poses some unique challenges. First of all the substrate material has to survive in a space environment during its operational life time. Second, the lens material has to be light weight, packageable and deployable in space. Give these requirements, we have selected 0.7 mm thin glass sheets as a baseline material for fabricating a 5-m diameter foldable Fresnel lens. These glass sheets are produced in high volume for use in flat-panel displays. The schematic of our 5-m diameter Fresnel lens is shown in figure 8. It consists of 81 panels each approximately 1 m wide that are patterned with the Fresnel lens pattern and are seamed together using metallic tabs. The particular pattern chosen is so that it can be folded into a 'hat-box' like shape for launch. Some of the folding sequence is also shown in figure 8.

Figure 7. Picture of a 50-cm diameter Fresnel lens binary mask

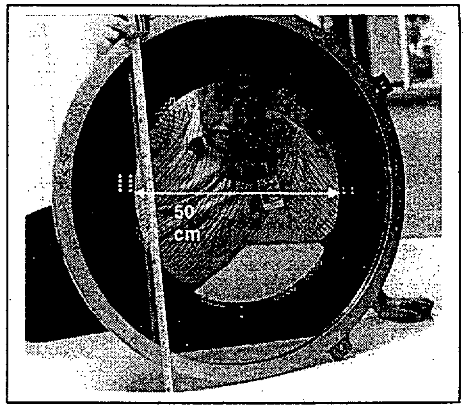
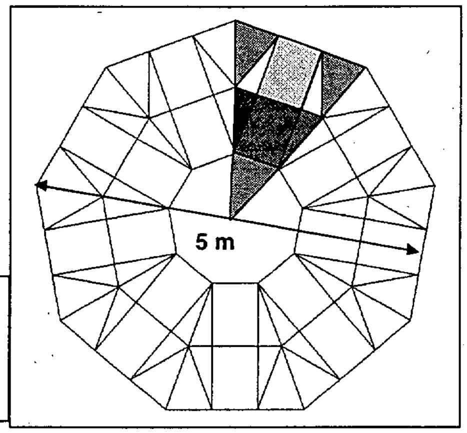
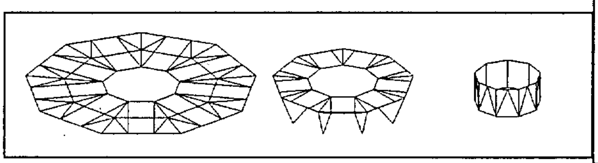


Figure 8. Schematic of a 5-m diameter foldable Fresnel lens. Some of the steps in the folding sequence are shown below.





In order to demonstrate the concept of a seamed lens, we built a 6 segmented 75 cm diameter lens and measured its focusing properties. The glass substrates consisted of 1 mm thick fused silica polished to 1/10 th wave transmission wavefront. The Fresnel lens was patterned on each panel separately and the panels were aligned to each other using fiducial marks and seamed together using metal tabs. The seamed lens is shown in figure 9. The nearly diffraction limited focal spot produced by this lens when illuminated by a collimated beam is shown in figure 10. This confirms that a seamled lens can act as a monolithic lens as long as it is precisely assembled. Following this measurement, we removed the lens from the mount, folded it, unfolded it and placed it back in the mount and measured the focal spot again. This image is also shown in figure 10. The similarity of the focal spots before and after the folding confirms the validity of the concept of a folding lens for space telescopes. We are currently building a 5-m diameter segmented Fresnel lens.

Summary

In summary, we have briefly discussed the need for large aperture diffractive optics in high-power laser and space applications. In responding to these needs we have developed over the last several years unique fabrication capabilities for manufacturing diffractive optics at ~ 1-m sizes. Finally we illustrated these capabilities with selective examples of diffraction gratings and Fresnel lenses. Currently we are applying this technology for fabricating even larger aperture diffractive optics.

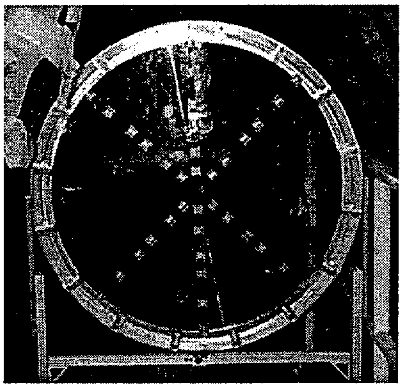


Figure 9. Picture of the 6-segmented seamed Fresnel lens. The radially distributed shiny squares are the metallic seaming tabs.

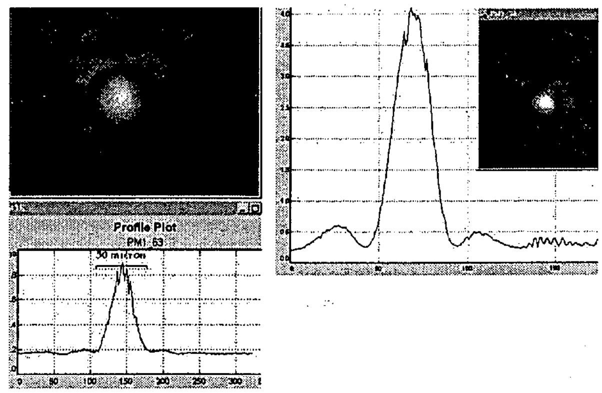


Figure 10. The focal spots produced by the segmented Fresnel lens in the initial assembly shown in figure 9 before folding (left image) and after a folding and an unfolding cycle (right image)

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