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Use of dome (meniscus) lenses to eliminate birefringence
and tensile stresses in spatial filters for the Nova laser

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ABSTRACT

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We document the concept and the design method for dome lenses that have a compressive pressure applied to the periphery. Dome (meniscus) lenses can eliminate both birefringence and tensile stresses if used in evacuated spatial filters where a pressure difference is present across the lenses. Calculations show that spatial filter birefringence is an insignificant 3 nm within the portion of a 740-mm Nova spatial filter dome lens illuminated by the laser beam. Membrane stresses are everywhere compressive, varying from -1.2 to -2.4 MPa, and are nearly uniform over the illuminated portion of the lens.

Eliminating sources of birefringence on the Nova laser could increase the energy on target with Type II/Type II frequency conversion from ~50% to the ~70% level attainable with Type I/Type II frequency conversion. Eliminating tensile stresses may reduce the damage and catastrophic failure that has occurred in some Nova spatial filter input lenses. The major disadvantage of using dome lenses on Nova is the cost of new lenses which could range up to \$50,000 per lens for the material and \$20,000 per lens for finishing.

1. INTRODUCTION

Experiments^{1,2} on the Nova laser have shown that the efficiency of Type II/Type II third harmonic (3ω) generation can approach 68% if the laser beam is well polarized, say along the horizontal direction. This efficiency is similar³ to that obtained with Type I/Type II frequency conversion. Unfortunately, experiments⁴ also show that the efficiency of Type II/Type II frequency conversion drops to ~45% with when as little as 1.7% of the beam energy is polarized vertically rather than horizontally. Even lower efficiencies are predicted if depolarization exists at 1ω input intensities exceeding 25 TW/m². Measurements⁵ on Nova indicate that, on the average, the 460-mm amplifiers alone depolarize about 0.5% of the energy and the 315/460-mm spatial filters

alone depolarize about 0.6% of the energy. The depolarization is distributed nonuniformly throughout the beam and averages about 2% of the total beam energy. We infer that the depolarization in the 460/740-mm spatial filters must be substantial. If all of the depolarization can be eliminated, then both the 3ω frequency conversion efficiency and the usable energy on target could be increased.

Depolarization in the spatial filters comes mainly from stress-induced birefringence. The stress is caused by the atmospheric pressure difference across the lenses. There are at least two ways to reduce the birefringence: reverse the spatial filter output lens; and use a dome lens.

2. REVERSED OUTPUT LENS

Seppala^{6,7} has suggested that birefringence, and hence depolarization, can be reduced by reversing the spatial filter output lenses so that the vacuum face becomes the pressure face. Seppala used stress calculations by Bumpas⁸ that showed that reversing the output lens changed the sign of the birefringence without changing the magnitude significantly. On the Nova 460/740-mm spatial filter we predicted that this change would reduce the birefringence from 120 to 35 nm. At these low levels, depolarization is proportional to the square of the birefringence, so that the depolarization in the spatial filter could be reduced by over an order of magnitude.

A similar improvement is feasible in the 315/460-mm spatial filter, but it is not known if reversing the output lens would have a significant effect because the 460-mm amplifier disks are positioned at Brewster's angle and act as polarizers themselves. Hence, any depolarization in the 315/460 mm spatial filter may already be reduced as the laser beam passes through the 460-mm amplifiers. The net result is that the total Nova depolarization could be reduced from about 2% to 0.5%, which is that present in the 460-mm amplifiers alone, by reversing the 460/740-mm output lenses.

Although Seppala's suggestion is simple and inexpensive, it adds spherical aberration of 0.6 to 0.7 wavelengths unless the lenses are refigured. Spherical aberration can decrease the 3ω frequency conversion efficiency, but the magnitude of the decrease is expected to be small.

Tests⁹ on one of the Nova beamlines have shown a reduction in the average amount of depolarization by reversing the spatial filter lenses, but there was no significant improvement in conversion efficiency. Future measurements on the point-by-point distribution of the polarization vector may explain why this is so.

3. DOME LENSES

An alternative to Seppala's solution is to replace the present spatial filter lenses with dome (meniscus) lenses, supported in such a way that the birefringence is negligible and only compressive stresses exist. Our concept (Fig. 1) uses the fact that in a spherical vacuum chamber, the membrane stresses in the wall are equal in all directions--that is, the stresses parallel to the surfaces of the chamber in the longitudinal and latitudinal directions are equal ($\sigma_\phi = \sigma_\theta$). In a spherical vacuum chamber, the membrane stresses are the principal stresses, and under external pressure loading they are compressive. The dome lens (Fig. 1) resists the atmospheric pressure difference across it by a normal O-ring support having a total force F_x . However, we apply an additional compressive force F_y around the periphery of the lens by inflating a toroidal bladder similar to that used in lens transportation fixtures. The magnitude of F_y is adjusted by varying the gas pressure inside the bladder so that the resultant force $F_x + F_y$ is parallel to the lens surfaces. The lens now has the same net support forces as if it were part of a spherical vacuum chamber and hence has the same equal membrane-like stress distribution.

Figure 1. Membrane stresses are identical in all directions and are compressive (i.e. < 0) in a spherical vacuum chamber (a) so the birefringence β is identically zero. Compressive forces can be added to the periphery of a dome lens (b) so that the support is identical to that in a segment of a spherical vacuum chamber, which eliminates both birefringence and tensile stresses.

The birefringence β is found by integrating principal stresses along the path of a light ray through the thickness of the lens. Its value is

$$\beta = \int_{r_i}^{r_o} B (\sigma_\phi - \sigma_\theta) dr ,$$

where B is the stress-optic coefficient, equal to $3.5 \times 10^{-12} \text{ m}^2/\text{N}$ for fused silica,¹⁰ and r_i and r_o are the inner and outer radii of the lens as shown in Fig. 1. Because $\sigma_\phi = \sigma_\theta$ throughout the lens, $\beta = 0$ for any path of the light through the lens.

Actual spatial filter lenses have a different design than that shown in Fig. 1 in that the thickness varies from the lens centerline (axis) to the periphery. A general closed-form solution of the stress field does not exist for a variable thickness lens. Bumpas⁸ used the GEMINI¹¹ linear-elastic finite-element computer code to calculate the stress field in an actual dome lens and also calculated the birefringence by integrating the stresses axially through the thickness. There are two minor sources of error in performing the integration in this manner. First, the integration does not follow the exact path of a refracted light ray through the lens. Second, the longitudinal stress calculated with GEMINI, and used in the equation above, is always in the direction present at the axis of the lens and does not change direction at locations closer to the periphery of the lens. However, our lens curvature is small and this constant-direction longitudinal stress, which we term σ_ϕ' , has nearly the same magnitude as σ_ϕ . Further, GEMINI results show that even for a dome lens with varying thickness and with peripheral loading, σ_ϕ' is close to σ_θ . We therefore infer that any error in calculating β because the integration path is axial rather than along the path of a refracted light ray or because σ_ϕ is slightly different than σ_ϕ' is negligible and that β is still nearly zero over the entire lens surface illuminated by the laser beam.

A dome lens with peripheral loading has the additional advantage that the stresses are everywhere compressive. Each spatial filter lens has one face in tension because of the atmospheric pressure difference across the lens. Brittle materials such as fused silica are strong in compression and weak in tension. Fractures can propagate if the stress field is tensile, but generally do not propagate when the stress field is compressive. Thus, the spread of the initial damage and the probability of failure are reduced when the stress field is compressive. No matter how an initial damage site occurs, crack propagation into undamaged regions is likely if the damaged surface is under tension, and the area of damage can spread with each successive laser shot.

Damage has occurred in Nova spatial filter input lenses at average fluences lower than the expected damage threshold of fused silica. The damage was first observed in near-field photographs for a Nova beamline as small damage sites on the downstream face of the input lenses, which are exposed to higher fluences than the output lenses. Experiments confirmed that the damage sites were at the location of intensity spikes in the Nova beam profile that exceeded the damage threshold. The damage sites grew with successive shots. A photograph of a damage site on a 460-mm spatial filter input lens is shown in Fig. 2. The damaged input lenses were removed when the diffraction ripples caused by the damage sites became strong enough to significantly damage downstream optical components. Most input lenses fractured into two pieces along a line through a damage site when air was admitted to the spatial filters before lens removal [Fig. 2(b)]. We do not understand the exact mechanisms that produce this catastrophic failure, but using dome lenses that have a compressive static stress field would reduce crack propagation and could prevent catastrophic damage during lens removal.

The major disadvantage of the dome lens concept is that new lenses would be needed. The cost¹² for the most expensive 740-mm output lens is about \$50,000 per lens for the material and \$20,000 per lens for finishing. Some savings may be

Figure 2. Photograph of (a) a damage spot and (b) a catastrophic crack in a 460-mm fused silica spatial filter lens. The crack propagated across the lens as air was admitted into the spatial filter prior to lens removal.

possible if the billet can be slumped so that its shape before polishing is close to the final shape. However, dome lenses would offer advantages if the spatial filter lenses are replaced for any reason. Increased coma, which occurs if dome lenses are used, will require more careful alignment but should not be a significant problem.

4. ANALYSIS

The compressive force required at the periphery of a dome lens to null the birefringence increases if the radius of curvature of the lens is increased. We first calculated the radius of curvature for a 740-mm (800-mm-diam.), constant thickness, output spatial filter lens that would require a uniform pressure P_y of 2.5 MPa around the periphery to null out the birefringence. The value of 2.5 MPa is somewhat arbitrary but we wanted it to be less than the 3.5 MPa maximum pressure used in the bladders of the Nova lens transportation fixtures. Optimization of this pressure and the associated radius of curvature remains to be completed. A high peripheral pressure results in a large lens radius of curvature, but the bow in the lens is small. Hence, less material is needed to manufacture the lens and cost is reduced. However, a high peripheral pressure requires more careful containment of the bladder, and there is a maximum practical pressure that can be used in a given bladder without the risk of a blowout.

Consider a dome lens with radius of curvature r , thickness $t = 45$ mm, and diameter $d = 800$ mm, as shown in Fig. 3. We chose these values of t and d because they are used in the present Nova 740-mm spatial filter output lens. The resultant force $F_x + F_y$ must be parallel to the surfaces of the lens at its periphery, so we have

$$\tan \phi = \frac{F_x}{F_y} = \frac{\pi P_a d^2 / 4}{\pi P_y d t} = \frac{P_a d}{4 P_y t}$$

and

$$r = \frac{d}{2 \sin \phi}$$

Under operating conditions, $P_a = 0.1$ MPa For $P_y = 2.5$ MPa, the value of d is 10° and hence $\phi = 2.3$ m.

Seppala¹³ used this value of r for the inside radius of curvature (the concave surface) and then calculated that the outside radius of curvature (the convex surface) had to be 1.7 m to match the spatial filter focal length of 15 m. Bumpas⁸ then used these dimensions and calculated the stress field, displacements, and

Figure 3. Schematic of a constant thickness dome spatial filter lens used to calculate the desired radius of curvature, r .

birefringence for peripheral pressures of zero and 2 MPa. With zero peripheral pressure, σ_θ and σ_ϕ' varied from -5 MPa (compression) on the pressure face to 4 MPa (tension) on the vacuum face. Birefringence varied almost linearly with radius from zero at the centerline to 300 nm at the edge of the beam, just inside the O-ring support. With 2 MPa peripheral pressure (see Figs. 4-6), the stresses were compressive and only varied from about -1.2 to -2.4 MPa. Maximum birefringence was an insignificant 3 nm in the region illuminated by the laser beam.

Figures 4 and 5 show values of σ_θ and σ_ϕ' . All of the stresses are compressive (negative), and the magnitude of the stresses is nearly the same at all locations except near the O-ring support. Stresses near the O-ring are outside the laser beam and do not contribute to birefringence. At any point on the centerline, the membrane stresses must be equal because of symmetry.

Birefringence at a 45° angle with respect to the polarization of the beam is shown in Fig. 6. Birefringence near the centerline is zero because, by symmetry, the membrane stresses are equal. The birefringence reaches a peak of only 3 nm inside the region illuminated by the laser beam. The higher birefringences near

Figure 4. Contours of stress in the θ direction, σ_θ , for a dome lens with a peripheral pressure of 2 MPa.

Figure 5. Contours of stress in the ϕ' direction, $\sigma_{\phi'}$, for a dome lens with a peripheral pressure of 2 MPa.

the O-ring support are outside the illuminated region and do not contribute to depolarization.

5. TESTING

If the dome lens concept is to be implemented on Nova or on a Nova upgrade, an experiment is needed to confirm the calculations. Figure 7 shows a scaled spatial filter with two dome lenses. The lenses would be perhaps 200 mm in diameter and could be made of acrylic or of fused silica. A vacuum would be applied between the lenses and the resulting stresses and birefringence

Figure 6. Birefringence β at 45° to the polarization axis for a dome lens with a peripheral pressure of 2 MPa.

Figure 7. Schematic of a scaled test of the dome lens concept.

measured. If fused silica is used, some information on the elimination of breakage could be obtained.

6. CONCLUSIONS

Use of dome (meniscus) lenses in spatial filters could eliminate birefringence and tensile stresses. Elimination of birefringence and the resulting beam depolarization has the potential of significantly increasing the useful energy on target in the Nova laser. Elimination of tensile stresses can reduce propagation of cracks caused by high-intensity spikes in the Nova beam and may eliminate catastrophic damage during lens removal. A disadvantage is the cost of new lenses. Increased coma which results with dome lenses should not be a significant problem.

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