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TO CRYOGENIC ICF TARGET CHARACTERIZATION

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APPLICATIONS OF HOLOGRAPHIC INTERFEROMETRY TO CRYOGENIC ICF TARGET CHARACTERIZATION*

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Uniformity of condensed layers of DT fuel in cryogenic ICF targets is a crucial parameter in their design. Measurement by classical interferometry lacks resolution to determine DT layer uniformity for targets with thick glass shells and/or thick ablative polymer coatings. We have developed holographic interferometry as an alternative tool for layer uniformity determination. This method is sensitive only to the fuel layer itself. We describe the technique and interference pattern analysis, and present preliminary results.

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I. INTRODUCTION

Thin solid layers of DT fuel have played a role in the conceptual designs of some laser fusion targets for more than a decade, and continue to do so. Typically such designs call for the cryogenic layer fuel to be frozen out on the interior of the fuel capsule. The fuel layer and the inner portion of the fuel capsule are then accelerated inward in reaction to the ablation of the outer portion of the capsule by the laser radiation. Since the fuel layer forms a part of the converging target shell, any fuel mass anisotropies could lead to Rayleigh-Taylor instabilities, just as will anisotropies of the "pusher" layer. It is therefore very important that we measure the fuel layer uniformity, particularly for highly convergent designs such as those under consideration at University of Rochester.¹

Classical interferometry has long been used to measure wall uniformity in transparent laser fusion targets. This is usually inadequate for fuel layers, however, due to both the very low refractive index of solid DT, and to the thinness of the fuel layer compared with the glass fuel capsule, and is even worse if the capsule has a thick polymer coating. Holographic interferometry, on the other hand, allows direct examination of the fuel layer alone, while largely neglecting

the fuel capsule. In this paper we discuss its use for fuel layer examination. In section II we give a simplified analysis of the fringe pattern in a holographic interferogram of a condensed DT layer, and compare it to a classical interferogram. In section III, we describe our interferometer and give some preliminary results of layering studies. In the last section we discuss the potentiality of the technique, and our plans for further work.

II. A Comparison of Classical and Holographic Interferograms of Transparent Targets

Holographic interferometry is not new, and many good references exist.² Basically, an interferogram is formed through the mixing of coherent light from an object with its own holographic reconstruction. If nothing changes in the object between making the hologram and reconstruction, the interferogram contains no fringes since the two beams are in phase everywhere. However, any change in the object leading to a change in optical path length, such as condensation of a fuel layer, will lead to interference fringes. These are due only to the change that has occurred in the object. To within an approximation that refraction is unimportant, the transparent fuel capsule plays no role.

We have studied DT layer formation by making a hologram of the target with the fuel in the gas phase (above 35 kelvins), and forming the interferogram with the fuel condensed - either solid or liquid. The fringe pattern is due to interference between light rays traversing the sphere of DT gas and those traversing an (essentially) evacuated DT shell. An exact investigation of the pattern could be carried out by using ray tracing codes, similarly to the work of Miller and Sollid.³ However, simple approximate results can be obtained from a model based upon a fuel layer consisting of offset spherical surfaces inside a perfect fuel capsule, as in Fig. 1a. Deviations from a perfect fuel layer are determined by the offset ϵ . We calculate phase shifts with this model assuming no refractive effects -- an approximation less and less valid for thicker fuel capsules and layers. This is very similar to the model of imperfect glass shells analyzed by Stone, Gregg and Souers,⁴ and by Weinstein and Hendricks.⁵

The relevant quantity for predicting the fringe pattern is the change in the optical path length between the gas-filled target and the layered target, which we call S . For a ray passing through the polar coordinates q, θ in the mid plane of the spherical target, and with the offset assumed to lie along the polar axis, we find

$$\frac{1}{2r} S(q, \theta, \epsilon) = (n_s - n_g) [1 - Q^2]^{\frac{1}{2}} - (n_s - 1) \left[\left(1 - \frac{\rho_g}{3\rho_s} \right)^2 - Q^2 - \epsilon^2 + 2\epsilon Q \cos \theta \right]^{\frac{1}{2}} \quad (1)$$

where Q and E are q/r and ϵ/r respectively, r is the outer radius of the fuel layer, and ρ_g, n_g and ρ_s, n_s are the densities and refractive indices of gas and solid DT respectively. In deriving this, we used that the inner radius of the layer is $(1-\rho_g/3\rho_s)^2$. Equation (1) is exact within our model and the no-refraction approximation.

Our expression for $S(Q, \theta, E)$ predicts basically circular fringes. This is apparent if $E=0$, since then S depends only on Q . In the spirit of Stone, Gregg and Souers, we can approximate values of Q giving π radians phase shift compared to the point of minimum phase shift (which is the center of the fringe pattern) by solving

$$S(Q, \theta, E) - S(Q_0, \theta_0, E) = \frac{\lambda}{2}$$

where λ is the wavelength of the analyzing laser. We calculate

$$Q_h = P + \frac{3}{4} E \frac{\rho_s}{\rho_g} \cos \theta \quad (2)$$

The subscript h indicates the holographic result. We have used that $n_{s,g} = 1 + k\rho_{s,g}$, k a constant. P is the value of Q_h for $E=0$ (a perfect layer), and is given by

$$P^2 = \frac{3\lambda}{8r(n_g - 1)} \quad (3)$$

Equation (2) is good to first order in E and for small Q_h . As pointed out by Stone, et al.⁴, Eq. (2) describes a nearly

circular fringe displaced from the center of the sphere by $3E\rho_s/4\rho_g$. This fringe-pattern shift can then experimentally be used to determine E .

The difference between holographic interferometry and classical single-pass interferometry is that for the latter, the transparent fuel capsule contributes its own phase shift. Assuming a perfectly uniform capsule with thickness t_0 and refractive index N , the optical path length change is now

$$S_c(Q, \theta, E) = S(Q, \theta, t) + (N-1) T (2+Q^2) \quad (4)$$

where $T = t/r$, Q is again assumed small, and T is assumed small. We then find

$$Q_c = P_c + E \frac{\rho_s}{\rho_g} \cos \theta / \left[\frac{4}{3} + \left(\frac{N-1}{n_g-1} \right) T \right] \quad (5)$$

with

$$P_c^2 = \frac{\lambda}{c (n_g-1) r \left[\frac{4}{3} + \left(\frac{N-1}{n_g-1} \right) T \right]} \quad (6)$$

Equations (2), (3), (5), and (6) provide a useful comparison between holographic and classical interferometry. As an example, we consider a 150 μm i.d. glass sphere 5 μm thick filled with DT at a density of 10mg/cc. A completely uniform layer formed from the fuel would have a thickness of 1.10 μm . For 633nm wavelength illumination and $\epsilon =$

0.2 μm , using the DT density data of Souers⁶ and assuming $N=1.5$, we find the following:

$$P = 0.67 \quad ; \quad Q_h - P = 0.046 \quad (\text{holographic})$$

$$P_c = 0.40 \quad ; \quad Q_c - P_c = 0.010 \quad (\text{Classical})$$

A numerical calculation of $Q_h - P$ directly from Eqn. (2) yields 0.041, which indicates the degree of approximation of the above results.

The point to be made is that determination of E from the holographic interferogram with 20% confidence limits requires measurement of $Q_h - P$ to 20%, or location of the center of the fringe pattern to about .01 of the sphere image radius. Since $\mu_g/3\mu_s = D = d/r$ where d is the fuel layer thickness, Eqn. (2) indicates that the fringe pattern center shift is $E/4D$, or one quarter of the "nonconcentricity" of the layer, independent of the fuel capsule thickness or index of refraction. Therefore nonconcentricities of 0.2 should always be measurable to 20% if the fringe pattern center can be localized to 1%. On the other hand the same accuracy from classical interferometry would require measurement of $Q_h - P$ to about .002 of the image radius. The situation will get worse for larger values of T , as in polymer coated targets. For 15 μm of index 1.5 polymer on the example target, $Q_c - P_c$ would be 3×10^{-3} .

III. Preliminary Results

To begin to explore holographic interferometry, we assembled the apparatus in Fig. 2. The heart of the system is a holographic camera⁷ based upon a thermoplastic recording principle which allows in-place exposure and development of a hologram in about 10 seconds. The thermoplastic holography plate has an optimal spatial frequency of 800 line pairs per mm, comparable to the best photographic film.

Representative holographic interferograms from our system are shown in Figures 1 and 3. The target of Fig. 1b is a glass sphere with 153 μm o.d. and 4.4 μm wall, filled with DT at a density of 10mg/cc and held at 25 kelvins. At this temperature, about 1 atmosphere of gas remains in the target, and after correcting for this we calculate the dark fringe radius to be 0.56 r, which agrees well with observations. The fuel is partially liquified and has formed a very nonuniform layer under gravitational pull. Eyeball estimate of the fringe center shift yields $Q_h - P = .14 \pm .04$, so from Eqn. (3), $e \approx 0.6 \pm 0.2 \mu\text{m}$.

Figure 1c is a 130 μm i.d. glass sphere with 5 μm walls, coated with 15 μm of fluorocarbon polymer, and a 10mg/cc DT fill. The target is held just below the triple

point, surrounded by 500 mTorr of helium gas. It had just been heat-pulsed by an Argon-Ion laser to flash evaporate the fuel, which has recondensed to a fairly uniform layer as indicated by the well-centered circular fringe. As far as the fringe pattern goes, the thick fuel capsule has indeed played no role.

Figure 3a is the same target as Fig. 1b, but we have introduced a constant phase gradient into the reference beam, resulting in the linear background fringes. A calculation of the fringe pattern using Eqn. 1 with $\epsilon \approx .6 \mu\text{m}$ is shown in Fig. 3(b). Again, the residual OT gas at 25 kelvins has been taken into account. The deviation of these fringes inside the target image give a direct measure of the layer thickness for every point where the fringes are visible. By measuring the fringe shift along the mid line of the target, and therefore the phase shift due to the fuel layering, we calculated the radial thickness profile of Fig. 4. We have assumed equal thickness on diametrically opposed sides of the target. For comparison we show the calculated layer thickness for the offset sphere model.

IV. Discussion and Conclusion

The above preliminary results are encouraging, but much remains to be done in developing this technique for cryogenic

laser fusion target studies. In future work we will determine the effects of refraction on the fringe pattern. These will play a larger role for thicker targets, as seen by comparing the limb shadows of Figures 1b and 1c. These shadows are produced by light refracted out of the entrance pupil of the viewing optics.

The holographic interferograms presented here were taken in the simplest possible manner. Holography can be extended in a number of ways to provide much richer data than optical path differences in a single direction. We plan on using sinusoidal phase gratings to simultaneously record optical path differences in several directions. We will also attempt to use diffuse light holography. While this introduces the problem of speckle, it provides the potential of measuring a truly three-dimensional distribution of fuel with a single hologram. This may also be possible by applying tomographic principles to multidirectional holography, as with the sinusoidal phase grating. We will utilize a.c. interferometric techniques to measure fringe positions for more accurate determinations of fuel distribution. This can be readily done by a simple phase modulation of the reference beam. Finally, by employing digital frame-grabbing techniques we will be able to subtract out unwanted shadowing and defects, to allow easier interpretation of interferograms.

In conclusion, we have demonstrated that holographic interferometry is a useful tool for measurement of fuel layer uniformity in transparent cryogenic laser fusion targets. Nonconcentricities of magnitude 0.2 should be measurable to 20% for all targets, while classical interferometry will approach this for only extremely thin fuel capsules. Holographic interferometry also offers the potential of more sophisticated techniques and analysis.

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7. The holographic camera is available from Newport Research Corporation.

Figure Captions

Fig. 1. (a) Model of a nonuniform fuel layer in a transparent target. (b) Interferogram of a liquid layer in a glass fuel capsule. (c) Interferogram of a solid layer in a polymer coated fuel capsule.

Fig. 2. Apparatus for studying cryogenic fuel layers using holographic interferometry.

Fig. 3. (a) Interferogram of liquid layer in a glass fuel capsule, with a constant phase gradient reference field. (b) Fringe pattern calculated for the target.

Fig. 4. Layer thickness determination from data of Fig. 3(a). o--measured thickness; solid line--calculated thickness for offset-sphere model.

(a)

(b)

(c)

Figure 1

Figure 2

(a)

(b)

Figure 3

Figure 4