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MEASUREMENT OF LASER FUSION CAPSULES USING THE INTERFEROMETER METHOD OF EXCESS FRACTIONS

Roger R. Stone

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LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California, 94550

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MEASUREMENT OF LASER FUSION CAPSULES USING THE INTERFEROMETER METHOD OF EXCESS FRACTIONS

Abstract

A system is proposed to allow use of the method of excess fractions with a high-power interference microscope. This allows the measurement of average wall thicknesses for small ($<200\text{-}\mu\text{m}$ o.d.,

and from 0.5- to $2.0\text{-}\mu\text{m}$ wall thicknesses) transparent laser fusion targets to better than 0.5% and wall uniformity to better than 0.3% . The DT gas fill of the capsules can be nondestructively measured to about $\pm 3\%$.

Introduction

The basic laser fusion capsule used at the Lawrence Livermore Laboratory and other labs is a small ($<200\text{-}\mu\text{m}$ -o.d.), transparent glass shell filled with equi-

molar DT. Figure 1 shows such a target. The walls of the capsule are from about 0.5 to $2.0\text{ }\mu\text{m}$ thick. Approximately two years ago, physics designers specified

Fig. 1. Typical DT-filled transparent glass shell target for laser fusion.

that it would be desirable to measure the wall thickness of the capsules to an accuracy of better than 1%. As a result of work at LLL by Gregg¹ and Stone, Gregg, and Souers,² using the interference properties of light, an accuracy of the average wall thickness measurement of about $\pm 5\%$ has been obtained. Researchers at Los Alamos Scientific Laboratories (LASL) and at KMSF have utilized x-ray microradiography for wall thickness measurements with an accuracy of about $\pm 0.2 \mu\text{m}$ for the shells of interest.³⁻⁵

This report discusses a technique using the method of excess fractions and a high-quality interference microscope to measure the average wall thickness to better than 0.5%. When further developed,

this technique will plot average wall thickness of the shell to better than 0.3% and determine wall uniformity to better than 0.3%. After considering the capabilities of this technique, the author feels that measurement of the wall dimensions of glass shells is no longer a theoretical problem but is now a practical problem of resources and determining whether or not a $\pm 0.5\%$ shell really exists.

Since the method of excess fractions is so accurate, it is possible to nondestructively determine the gas fill of the capsules to within about $\pm 3\%$ if proper measurement of the index of refraction of the glass and equimolar DT versus density α are made. This is possible because each combination of wall thickness and gas fill is unique regardless of diameter.

Method of Excess Fractions

Table 1 defines the symbols used in the following discussion. As shown by

Fig. 2, the height of a step can be measured under monochromatic light using light

Fig. 2. Interference pattern for a slowly increasing step. The left shows a typical step profile, the right, an actual pattern obtained in a Twyman-green interferometer from such a step.

Table 1. List of symbols.

N	Integer specifying number of fringes
f	Fraction of fringe
λ	Wavelength of light, μm
h	Height of step, μm
s	Optical path length, μm
S	Dimensionalized optical path length, (s/r_1)
r_1	Outside radius of shell, μm
r_2	Inside radius of shell, μm
R	Dimensionalized radius, r_2/r_1
ℓ	Wall thickness, μm
L	Dimensionalized wall thickness, ℓ/r_1
p	Planar radius, μm
P	Dimensionalized planar radius, p/r_1
n	Index of refraction, medium surrounding shell
n'	Index of refraction, shell material
n''	Index of refraction, medium inside shell
e	Offset of inner surface relative to outer
E	Dimensionalized offset, e/r_1
ρ	Density, kgm/m^3

interference by tracing a dark (minimum) or bright (maximum) path across the step. This gives the number of fringes N, plus the fraction f. The thickness is, therefore, $(N + f) \frac{\lambda}{2}$, where $\frac{\lambda}{2}$ is used because the light is reflected at the reference surface and traverses the height of the step twice. If

the edge at the step approaches 90° , the ability to trace the path of a maximum or minimum is lost as shown by Fig. 3. It is possible to measure the fraction f, but not the number of fringes N. If the height is not too great, it is possible to use white light interference to determine N. Also if it is possible to measure the step height by some other method accurate to some minimum $(N \frac{\lambda}{2})$, the fraction can be measured and the absolute height then calculated. Another method, used to measure the step height when the reference is lost, is to use several wavelengths of light. The fraction f is measured at each wavelength and the following can be written:

$$(N_1 + f_1) \frac{\lambda_1}{2} = h \quad (1)$$

$$(N_2 + f_2) \frac{\lambda_2}{2} = h \quad (2)$$

or

$$(N_1 + f_1) \lambda_1 = (N_2 + f_2) \lambda_2 \text{ \& } N_1 = \text{INT}^* \left[N_2 \frac{\lambda_2}{\lambda_1} \right] \quad (3)$$

* Take only the integer part of the real number.

Fig. 3. Interference pattern with sharp step. The left shows a typical step profile, and the right, a schematic of the interference pattern.

where $\lambda_1 < \lambda_2$. Values are assumed for N_2 , and N_1 is calculated. Then Eqs. (1) and (2) are solved by an iterative process until their difference is a minimum.

In practice, three different wavelengths are used and the step height is approximately known. This increases the accuracy of the method by assuring the solution converges at the proper location. For purposes of this report, it is assumed

that the fraction can be measured to 0.01, even though experimental data indicates an accuracy of 0.006 is easily obtained. Reference 6 indicates that measurement of the fraction to 0.1 is accomplished by eye and to 0.001 by photoelectric methods. Assuming a measurement to ± 0.01 of the fraction and the use of green light, we obtain an accuracy of about $\pm 0.0025 \mu\text{m}$ or 0.25% for a 1- μm step height.

Average Wall Thickness Measurement

For the shells in question, the ability to trace a dark or light interference band is lost due to the shape of the parts. It is not possible to use white light interference due to the limited coherence length of this source. For a step with exactly the same reflectance as the reference surface, it is possible to measure the fraction by determining the intensity of the light at a point on the step (B) opposite a point (A) on the reference as shown by Fig. 3. The intensity of the light reflecting off the step is compared with the intensity when the interference is at a maximum. One can tell if the light intensity is on the rising or falling part of the intensity curve by noting the position of the measurement relative to a maximum on the step. For the center of the glass shell, the absolute intensity of the light is impossible to measure and compare with the background because of scattering, reflection, and absorption. It is therefore advantageous to consider relative measurement, the technique discussed in this report. The interference pattern of the background surface is caused to "roll," i.e., go from

a maximum to a minimum, etc., while the relative intensities of the background and center of the shell are measured. Figure 4 illustrates this situation. The background pattern appears to go from right to left. The frequency of the light intensity versus time of the center of the shell is exactly the same as that of the background surface interference pattern. Using light intensity plots of the background surface and that obtained at the center of the transparent shell, the phase or fraction can be determined. This is measured using three different wavelengths. The approximate thickness of the middle of the shell is obtained by using the interference pattern as described by Ref. 2. Knowing the fractions of the three wavelengths, it is possible to solve for N_1 , N_2 , and N_3 . This allows a path length difference between the center of the shell and a ray from the reference mirror, M1, to be determined. As shown by Fig. 5, and neglecting refraction, this difference is:

$$\Delta s_0 = s_0 - s_{\text{Ref}} = 4(r_1 - r_2) \\ \times n' + 4r_2 n'' - 4r_1 n \quad (4)$$

$$(N + f)\lambda = \Delta S_0 \text{ and } r_1 - r_2 = \ell. \quad (5)$$

Divide by r_1 to dimensionlize:

Fig. 4. Background and shell interference appearance as pattern is caused to roll. Fraction at center of shell is about 0.7.

$$(N + f) \frac{\lambda}{r_1} = \Delta S_0$$

$$= 4[Ln' + (1 - L)n''] \sim n] \quad (6)$$

or

$$L = \frac{(N + f) \frac{\lambda}{4r_1} - (n'' - n)}{n' - n''}. \quad (7)$$

If $n = n'' = 1.00$,

$$L = \frac{(N + f) \frac{\lambda}{4r_1}}{n' - 1}. \quad (8)$$

An estimate of the accuracy of the average wall thickness can be arrived at as follows:

$$L = g(f, \lambda, n')$$

$$\frac{dL}{L} = \left[\frac{\partial L}{\partial f} df + \frac{\partial L}{\partial \lambda} d\lambda + \frac{\partial L}{\partial n'} dn' \right] /$$

$$\left[\frac{(N + f) \frac{\lambda}{4r_1}}{n' - 1} \right]. \quad (9)$$

Fig. 5. Schematic of transparent shell with light ray through the center.

$$\frac{dL}{L} = \frac{df}{(N+f)} + \frac{d\lambda}{\lambda} + \frac{dn'}{n' - 1}. \quad (10) \quad \text{or}$$

As an example, assume:

$$r_1 = 20 \mu\text{m}$$

$$l = 1.0 \mu\text{m}, L = 0.05$$

$$n' = 1.5$$

$$df = 0.01$$

$$d\lambda \sim 10^{-5} \mu\text{m}$$

$$\lambda \sim 0.5 \mu\text{m}$$

$$dn' = 0.001$$

$$N + f = 4.00$$

$$\frac{dL}{L} \sim 0.005, \text{ i.e., } 0.5\%$$

Since this error comes primarily from the error in the fraction and index of refraction measurements, it is felt that this estimate of maximum error is very conservative. The error in these two measurements can be easily decreased by a factor of two.

Shell Wall Uniformity

The determination of shell wall uniformity involves measuring optical path lengths at the shell center and away from the center or making two measurements equidistant from the center. Referring to Fig. 6, the optical path length of an

arbitrary incoming ray can be written for a normalized transparent shell.

$$S_P = 4\{(1 - Y_0)n + (Y_0 - Y_i)n' + Y_i n''\}. \quad (11)$$

$$\text{Let } n = n'' = 1.00,$$

$$S_P = 4\{1 + (n' - 1)(Y_0 - Y_i)\}. \quad (12)$$

At the center, $P = 0$, $Y_0 = 1$,

$$S_0 = 4\{1 + (n' - 1)(1 - Y_i)\}. \quad (13)$$

If the shell were perfect,

$$Y_i = R \text{ at } P = 0.$$

Assuming a perfect shell, the optical path length at P can be calculated and compared to that actually measured. For an offset inner surface,

$$S_P = 4\left\{1 + (n' - 1)\left[(1 - P^2)^{1/2} - \left[R^2 - (P - E)^2\right]^{1/2}\right]\right\}, \quad (14)$$

and for perfect shell,

Fig. 6. Schematic of transparent shell with nonuniform walls.

$$S_P^+ = 4 \left[1 + (n' - 1) \left[(1 - P^2)^{1/2} - (R^2 - P^2)^{1/2} \right] \right] \quad (15)$$

To estimate the accuracy of such a measurement, assume the following:

$$\begin{aligned} r_1 &= 20 \text{ } \mu\text{m} \\ \ell &= 1.0 \text{ } \mu\text{m}, \\ R &= 0.95 \\ P &= 0.51 \\ n' &= 1.5, \end{aligned}$$

then

$$S_P^+ = 4.1174 \quad \text{or} \quad S_P^- = 82.3470$$

$$(N + f)_P = 4.3866 \sim 4.39.$$

Let $(N + f)_P = 4.40$; i.e., $\Delta f = 0.01$,

$$S_P = 4.1177$$

Solving for E:

$$E = 0.00028 \quad \text{or} \quad e \sim 0.0056 \text{ } \mu\text{m}.$$

It is possible to easily detect an offset of $\sim 0.006 \text{ } \mu\text{m}$. A more accurate method

would be to measure the fraction $-P$ relative to $+P$. Since the offset increases the optical path length at $+P$ and decreases it at $-P$, a smaller offset can be measured. For example:

Let

$$\begin{aligned} P &= \pm 0.51 \\ R &= 0.95 \\ \Delta f &= 0.01 \\ r_1 &= 20 \text{ } \mu\text{m} \\ n' &= 1.5 \end{aligned}$$

$$\Delta S_P = S_P^- - S_P^+ = 2 \left[\left[R^2 - (P - E)^2 \right]^{1/2} - \left[R^2 - (-P - E)^2 \right]^{1/2} \right] \quad (16)$$

For the example given, $\Delta S_P = 1.338 \times 10^{-4}$.

Solving for E:

$$E \sim 0.00011 \quad \text{or} \quad e \sim 0.0022 \text{ } \mu\text{m}.$$

The wall uniformity can be specified to be better than 0.22%.

Equipment

The following equipment is required to utilize the described method:

- A moving reference surface M1 to cause the interference pattern to "roll" on the background surface M2.
- A high-quality interference microscope.
- Pickup probes for the background surface and light intensity variations at the center of the shell.
- Amplification circuitry for the light pickups.
- Some means of recording light intensity versus time for all pickups.

or an interface to some machine capability.

A schematic of a system is shown by Fig. 7. The microscope used is a high-quality Zeiss* with a Twyman-Green two-arm interference system. It has matched objectives in the two arms and these are normally focussed onto two reflecting surfaces. In Fig. 7, these surfaces are

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

designated M1, reference mirror, and M2, test or background mirror. Total magnifications of 100X, 250X, and 600X are normally available for visual work with image plane magnifications of 10X, 25X, and 60X available. At LLL, M1 is

normally a reflecting stage micrometer and objective 1 is focussed onto its surface. This provides calibration marks for all work. M2 is then moved to the focus of objective 2 by means of a small X, Y, and Z stage mounted on the microscope.

Fig. 7. Schematic of system necessary to measure excess fractions under an interference microscope.

The pattern driver will cause M1 to move up or down at a rate controlled by the function generator and HV operational amplifier. The driver transducer is a piezoelectric-crystal micrometer assembly with movements of $5.5 \mu\text{m}/1000 \text{ V}$ or $15 \mu\text{m}/1000 \text{ V}$. A ramp signal is input to the amplifier and causes M1 to be driven at a constant rate. For each $\frac{\lambda}{2}$ of movement in either direction, the background pattern will shift a full fringe. For a given point, the intensity of light versus time will be sinusoidal.

Three different wavelengths are required for the system. The microscope has a 535.05-nm thallium light available. A 632.8-nm He-Ne and a 441.6-nm He-cd provide the other two wavelengths. Two movable mirrors are required to provide wavelength selection. Since the laser light is extremely coherent, interference will occur at each reflection within the microscope optics, and thus it is necessary to decrease the light's coherence before it enters the microscope. A method suggested by J. Bryan can be used which is to shine the light on a thin, spinning, frosted wheel. This wheel will be located at the focal point of the microscope condensing lens.

The light pickups are three 50- μm glass fibers located in the image plane of the microscope. The arrangement of the fibers is shown in Fig. 7. The two outside fibers, 2 and 3, are used to insure the interference pattern is oriented properly with respect to the two actual measuring fibers, 2 and 1. When the background pattern is in the correct orientation and moving past the fibers, the output of 2 and 3 will peak at exactly the same time. The center of the shell

to be measured is placed under fiber 1. As the pattern driver causes the background to roll, the signals from 1 and 2 are recorded and their phase difference can be determined.

The signals from the fibers are conducted to three separate photo tubes. Amplification and some signal processing is accomplished by the photo tube, amplifier arrangement. The output available from the amplifiers can be either analogue or BCD. Light fiber 1 can be movable in the image plane. The use of such capability will be discussed later.

The recording or measuring system in the simplest form is a three channel recorder. By recording signals 2 and 3, it isn't necessary to exactly orient the background, as a line can be drawn between the peak of the two signals and the actual background reference signal at the shell center can be determined. By measuring the time of the occurrence of the background peaks and the peak of the signal from 1, the phase between the two signals can be determined. This type of measuring scheme is very desirable as one is not concerned with the absolute light intensity values, but only the occurrence of peaks or where the signal crosses the axis. The frequency of the signal from channels 1, 2, and 3 will always be exactly the same.

It is possible to automatically process the signal out of the amplifiers in several ways. One would be to use an electronic counter that turns on at the peak of signal 2 and off at the peak of signal 1. Another counter would count between the successive peaks of signal 2. By dividing the first count by the second, the excess

fraction can be determined. In practice the average of about 10 cycles would be measured. By interfacing with a computer, total signal processing and subsequent

calculations became available. This type of capability may be required in determining gas fill which will be discussed later.

Production Usage

In practice, the operator would adjust the background pattern until broad interference bands are visible. The center of the transparent shell to be measured is positioned under fiber 1. A wavelength is selected and the pattern driver is turned on. As the bands pass, fibers 2 and 3 are adjusted so that their signals peak

simultaneously. Now the signals from all three fibers can be recorded. Another wavelength is selected and the process is repeated.

After the excess fractions have been determined for the three wavelengths, one can specify the range of N values since the approximate wall thickness is

Example: Let $r_1 = 20 \mu\text{m}$, $l = 1.0 \mu\text{m}$, $n' = 1.500 \pm 0.2 \mu\text{m}$

$$f_1 = 0.52$$

$$f_2 = 0.73$$

$$f_3 = 0.15$$

$$3 \leq N_1 \leq 5$$

$$\text{From scale } N_1 = 4, N_2 = 3, N_3 = 3$$

$$\text{Thus, } l = 0.9980$$

Fig. 8. Scale to be used to determine N_1 for wavelengths of 0.4416, 0.53505, and 0.6328 μm .

known. The simplest method of determining N_1 , N_2 , and N_3 is to use a scale as shown in Fig. 8. Once any N_i is determined, the actual path length is known. This can then be converted to average wall thickness using Eq. (8). Since light fiber 1 can be moved to any

point on the shell, it can be moved to say a planar radius of one-half the radius on both sides of the shell center and the path lengths of these two points compared. If they are not equal, the walls are not uniform. By rolling the ball, a higher overall accuracy on the ball specification can be made.

Gas Fill Determination

Determination of the DT fill is an important part of characterizing the target capsule. Researchers at KMSF measure the gas fill by breaking a statistical sample of shells after filling. The total gas pressure is determined by rupturing a shell in glycerol and measuring the diameter of the bubble formed. The quantity of tritium is determined by measuring total radioactivity of the gas from a broken shell in an ionization chamber and DT ratios are provided by a mass spectrometer.⁷ A nondestructive check of the existence of gas fill is accomplished prior to target firing by freezing the gas and optically measuring the frozen DT. Target fabricators at LASL have reported three methods of determining gas fill. One uses a 2.754-MeV gamma ray source (^{24}Na) and the resulting 0.26-MeV neutrons from the deuterium atom are counted (^{24}Na , $D(\gamma, n)$). The accuracy of such a scheme is reported to be $\pm 5\%$.⁸ Another technique used is to bombard the filled capsules with a 16.2-MeV proton beam from a Van de Graaff accelerator and measure the resulting deuterons and tritons. An accuracy of $\pm 10\%$ is reported using this technique.⁹ LASL and LLL both use the measurement of x rays emitted from the

shell walls as a result of tritium beta bombardment.^{10,11} A gas proportional counter is used at both labs with an accuracy of about $\pm 10\%$ for the fills of interest.^{3,12}

This report discusses using the method of exact fractions to measure gas fill. For the technique to be successful, it is necessary to measure the index of refraction versus density for the gas mixtures of interest.

Referring to Fig. 9 and neglecting the effects of refraction at the interfaces, we can write:

$$S_P = 4 \left\{ n \left[1 - (1 - P^2)^{1/2} \right] + n' \left[(1 - P^2)^{1/2} - \left[(1 - L)^2 - P^2 \right]^{1/2} \right] + n'' \left[(1 - L)^2 - P^2 \right]^{1/2} \right\}. \quad (17)$$

This is the "simple theory" described by Ref. 2. For $P = 0$ (center of shell), this reduces to:

$$S_0 = 4 \left[L n' + (1 - L) n'' \right]. \quad (18)$$

Rearranging:

$$L = \left(\frac{S_0}{4} - n'' \right) / (n' - n'') \quad (19)$$

or

$$n'' = \left(\frac{S_0}{4} - Ln \right) / (1 - L). \quad (20)$$

It is known that for gas, $n'' = f(\rho)$. It is therefore, necessary to measure the index of refraction of equimolar DT versus density. This has been accomplished for normal hydrogen with results shown by Fig. 10.¹³ This data will be used later to illustrate the powerfulness of the proposed system.

The simplest way to determine the gas fill is to measure the optical path length at the shell center prior to filling. The value of L is calculated from Eq. (8). After filling, the optical path length is again measured at the center of the shell. The increase in this path length will be due to the increase of n'' , the index of refraction of the inner filled space. Knowing L and S_0 , n'' can be determined by Eq. (20). The density of the gas can

Fig. 9. Schematic of transparent shell with arbitrary incoming light ray and neglecting refractive effects.

Fig. 10. Refractive index versus density for normal hydrogen at 298.15 K.¹³

then be read off of a chart or calculated using an equation which relates density to index of refraction. This method takes advantage of the fact that all measurements are taken at the shell center, therefore, refraction is not considered.

Due to handling considerations, it is desirable to perform all measurements on the shell after filling. This decreases the number of shells to be individually handled and requires only one setup under the microscope. For a previously filled shell, there are an infinite combination of L and n'' that will give the same optical path length at the center of the shell. There are certain restrictions on the relative values of L and n'' . These are:

$$n'' > \frac{S_0}{4}.$$

If

$$n'' = \frac{S_0}{4},$$

Fig. 11. Ratio of wall-to-gas fill optical path length contribution versus planar radius.

then

$L = 0$, i.e., no wall.

And

$$L \leq \frac{S_0 - 1}{n'' - 1} \text{ since } n'' \geq 1.00.$$

It is instructive to consider the contribution to path length of the shell walls relative to the gas fill. Figure 11 shows such a comparison for:

$$R = \frac{S_{\text{wall}}}{S_{\text{fill}}}. \quad (21)$$

Note that as P increases, the contribution to the total path length by the wall changes. This change in relative contribution is unique for any combination of L, n'' , and outside diameter. It is this fact that allows the gas fill to be determined. Table 2 lists additional comparisons and

Table 2. Ratio of wall contribution to inner fill contribution: ratio = $S_{\text{wall}}/S_{\text{fill}}$.

For: $L = 0.05$, $R = 0.95$
 $n' = 1.5$, $n'' = 1.00$ (no fill)

P	Simple ^a ratio	Code ^b ratio
0	0.07895	0.07895
0.2	0.08251	0.08173
0.37	0.09265	0.08956
0.51	0.10981	0.10274

For: $L = 0.05$, $R = 0.95$
 $n' = 1.5$, $n'' = 1.005$

P	Simple ratio	Code ratio
0	0.07855	0.07855
0.2	0.08210	0.08124
0.37	0.09219	0.08875
0.51	0.10926	0.10122

For: $L = 0.05$, $R = 0.95$
 $n' = 1.5$, $n'' = 1.0051$

P	Simple ratio	Code ratio
0	0.07855	0.07855
0.2	0.08209	0.08123
0.37	0.09218	0.08874
0.51	0.10925	0.10119

For: $L = 0.055$, $R = 0.945$
 $n' = 1.5$, $n'' = 1.005$

P	Simple ratio	Code ratio
0	0.09687	0.08687
0.2	0.09082	0.08989
0.37	0.10209	0.09838
0.51	0.12121	0.11259

^aNeglect effect of refraction.

^bRay trace code results.

Table 3. Example fraction measurements at $P = 0.51$ and constant S_0 and outside diameter.

Shell	L	n''	S_0	$(N + f)_0$	$S_{0.51}$	$(N + f)_{0.51}$
1	0.05	1.005	4.1190	4.44818	4.133382	4.9858
2	0.0503	1.00484	4.1190	4.44818	4.133585	4.9933
3	0.0496	1.00521	4.1190	4.44818	4.133111	4.9757

shows results of a ray trace code that includes refraction.

If the capsule is filled and S_0 at the shell is determined, one does not know the average wall thickness since n'' is not known. Given S_0 one can then measure S_p at a P of, say 0.51, and another path length is determined. There is only one combination of L and n'' that will give the two measured path lengths; therefore, both values are now known. Knowing n'' allows determination of the gas fill if n'' versus density has been previously measured.

An illustration of certain combinations of outside diameter, wall thickness, and fill will make the method clearer. It will be assumed that the fill is hydrogen since index of refraction data is available as shown by Fig. 10. The equation for the straight line relationship is:

$$n'' = 1.000 + 1.55347 \times 10^{-3} \rho, \quad (22)$$

where

$$\rho \text{ is in kg/m}^3.$$

It is further assumed that the excess fraction can be determined to 1/100. This is conservative. Green light with a wavelength of 535.05 nm is used for the examples.

Given a measurement of S_0 , there are three variables to consider: the outside diameter, the wall thickness, and the

index of refraction (gas fill). First consider three shells (1, 2, and 3) with equal outside diameters. If $n''_1 \neq n''_2 \neq n''_3$ and $S_{01} = S_{02} = S_{03}$, then $L_1 \neq L_2 \neq L_3$. For example:

$$\begin{aligned} S_0 &= 4.1190 \quad (\text{Nominal } 40\text{-}\mu\text{m} \\ &\quad \text{o.d. with } \ell = 1.0 \\ &\quad \mu\text{m and } n'' \\ (N + f)_0 &= 4.44818. \quad = 1.005 \mu\text{m}) \end{aligned}$$

Results are given in Table 3.

Note that for a change in L and the corresponding change in n'' , the fraction measured at $P = 0.51$ is different. Each change in L of about ± 0.0004 causes about a ± 0.01 fraction change at $P = 0.51$. Now this corresponds to an n'' change of about ± 0.0002 . A change in n'' of ± 0.0002 equals a change in density of about $\pm 0.1 \text{ kg/m}^3$. For the fill assumed ($\sim 3.3 \text{ kg/m}^3$), this is about $\pm 3\%$.

The other possibility for a known S_0 is a change in the outside diameter of the shell. Again assume:

$$\begin{aligned} S_0 &= 4.1190 \text{ and an outside diameter} \\ &= 41 \mu\text{m}. \end{aligned}$$

Results are given in Table 4.

Table 4. Example fraction measurements at $P = 0.51$ and a constant S_0 , but a different outside diameter.

L	n''	S_0	$(N + f)_0$	$(N + f)_{0.51}$
0.05	1.00424	4.1190	4.1161	5.0166
0.0486	1.00521	4.1190	4.1161	5.1003

Again $(N + f)_{0.51}$ is different for each L and n" combination and also different from the shell with a 40- μ m o.d. In practice, the outside diameter can be

measured easily to ± 0.5 to 0.7μ m on a production basis and to $\pm 0.1 \mu$ m using a TEM (transmission electron microscope).

Conclusions

The system described allows use of the method of excess fractions with a high-quality interference microscope. This provides the capability to measure the average wall thickness of laser fusion transparent shells to better than 0.5% and

wall uniformity to better than 0.3%. Although only details for characterizing laser targets have been covered, the system would be useful for many types of measurements where high magnifications are required.

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