Optical thickness measurement of substrates using a transmitted wavefront test at two wavelengths to average out multiple reflection errors

Peter de Groot

Zygo Corporation, Middlefield, CT 06457

ABSTRACT

I measure the optical thickness of thin substrates using a transmitted wavefront test in which the object is placed inside a Fizeau cavity comprised of a reference flat and a mechanically actuated transmission flat for phase shifting interferometry (PSI). Traditionally, this test had been complicated by the unwanted secondary reflections between the object surfaces even when the object is tilted. These reflections generate errors that are increasingly difficult to suppress as the substrate thickness decreases. The new technique involves two successive PSI measurements of the optical profile separated by a discrete change in source wavelength. The change in source wavelength is calculated so as to invert the error contributions from multiple surface reflections. Thus the average of the two measurements is relatively free of these error contributions.

Keywords: interferometry, phase measurement, wavelength scanning, optical thickness

BACKGROUND

A familiar problem in optical testing is the profiling of transparent objects having plane-parallel surfaces, which can generate unwanted multiple reflections in laser-based interferometers. Available solutions to this problem include white light,[1] grazing incidence,[2] desensitized grating interferometry,[3] the use of multimode laser diodes,[4] and combinations of measurements in different orientations.[5] A number of recent techniques are based on continuously tunable lasers,[6,7,8, 9] the most comprehensive of these being the Fourier-Transform or FTPSI technique introduced by Deck.[10]

The particular case of interest for this paper is the optical thickness, i.e. the physical thickness multiplied by the index of refraction, of substrates having two plane-parallel surfaces that are very close to each other, e.g. < 1mm. An accurate (1nm) optical thickness measurement is critical e.g. for the production testing of etalons for the telecommunications industries. Measurement of such thin plates using a continuously tunable laser are complicated by the very large tuning range, well in excess of 100GHz and approaching 1THz for 0.1-mm thick parts, required to separate the contributions from the various surface reflections. At present, a smooth, continuous laser tuning over this range is not easy to achieve with visible wavelength sources.

I propose here therefore a means to measure the optical thickness of thin parallel plates that also involves a wavelength shift to suppress unwanted reflections, but in this case, only a stepwise shift between two discrete wavelengths. Such a discrete change in wavelength is less demanding on the laser source and is therefore proposed as a meaningful alternative when a large continuous tuning range is impractical.

MEASUREMENT GEOMETRY

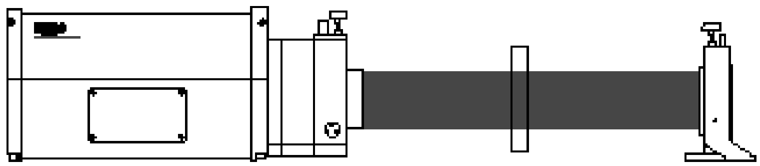


Figure 1: Familiar transmitted wavefront test geometry using a commercial laser Fizeau interferometer.

A useful geometry for optical thickness measurement is the transmitted wavefront test for a laser Fizeau interferometer (see Figure 1). In this familiar test, the first step is to characterize the Fizeau cavity comprised of a transmission flat (TF) and a reflectance flat (RF) only, without the object. The next step is to place the object or sample inside the cavity, tilted slightly to avoid direct, first-order reflections back into the interferometer imaging optics. Next is the measurement of the transmitted wavefront profile of the sample, which is approximately equal to the optical thickness of the object minus the physical thickness of the object. The measurement usually employs mechanical changes to the Fizeau cavity using PZT actuators, sufficient to shift the phase of the Fizeau cavity formed by the TF and the RF by e.g. 2π. Electronic image acquisition and data processing then yields the interference phase across the sample image. Using the transmitted wavefront profile, the known index of refraction of the object, and the known characteristics of the cavity, a computer calculates the optical thickness profile of the object.

Figure 1 would be already the end of the story were it not for errors related to the unwanted multiple reflections between the object surfaces, typically on the level of a few nm, which cannot be suppressed by tilting the sample. Figure 2 shows in somewhat greater detail the optical geometry with the addition of a wavelength-adjustable (but not necessarily continuously tunable) laser. The first-order reflected electric fields are E_{TF} and E_{RF} , as shown. These electric field interfere to create a field-dependent intensity variation at the CCD proportional to

$$I = 1 + V\cos(\theta) \tag{1}$$

where θ is the interference phase, V is the fringe visibility. The phase θ is linearly proportional to the round-trip optical path length from the TF to the RF:

$$\theta = \frac{2\pi\, OPL}{\lambda} \tag{2}$$

where λ is the laser wavelength. Note that there is an inherent 2-π ambiguity in the phase measurement, the field dependence of which may be eliminated using any one of the standard phase connect or unwrapping procedures.

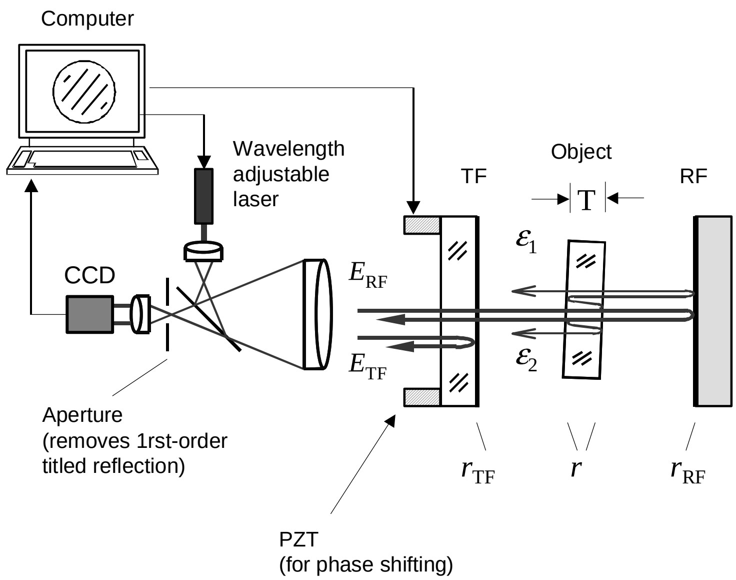


Figure 2: Schematic of transmitted wavefront geometry showing spurious reflected electric fields $\varepsilon_1, \varepsilon_2$ and the addition of a wavelength-adjustable laser source.

The usual transmitted wavefront procedure involves an initial calibration OPL_{cal} of the Fizeau cavity optical path length with the object removed. With the object in place, I measure a new path length OPL_{test} the optical thickness profile Z of the object is

$$Z = \frac{n}{2(n-1)}\left(OPL_{test} - OPL_{cal}\right). \tag{3}$$

There are however in addition to the desired electric fields E_{TF} and E_{RF}, two spurious electric fields $\varepsilon_1, \varepsilon_2$ resulting from internal reflections between the front and back object surfaces. For thin substrates (e.g. < 1mm) and nearly parallel TF and RF (e.g. < 10-μrad wedge), the spurious electric fields are nearly identical in phase and amplitude and one can set them to a common value ε:

$$\varepsilon_1 \approx \varepsilon_2 \equiv \varepsilon \tag{4}$$

The phase of the spurious fields relative to the desired field reflected from the RF is

$$\alpha = \arg(\varepsilon) - \arg(E_{RF}) \tag{5}$$

which evaluates to

$$\alpha = \frac{4\pi}{\lambda}(Z + nT) \tag{6}$$

where T is the nominal physical thickness of the object and Z is the field-dependent optical thickness profile, less the nominal value nT. The relative amplitude of the error term is

$$|\varepsilon| = r^2 |E_{RF}|. \tag{7}$$

where r is the surface reflectivity. The resulting error in the measured optical path difference caused by the sum of $\varepsilon_1, \varepsilon_2$ is therefore

$$\delta OPL \approx \frac{\lambda}{\pi} r^2 \sin(\alpha). \tag{8}$$

For a nominal laser wavelength of 633 nm and an amplitude reflectivity r of 20% for the object surfaces (typical of BK7 and fused silica glass), the peak-valley round-trip optical path error is 16 nm, much too large for precision testing. Further, for the case of thin plates, it is impractical to tilt the plates to attempt a cancellation of the errors according to the technique developed by Ai and Wyant for optical flats.[11]

Here I propose to suppress the error terms $\varepsilon_1, \varepsilon_2$ by means of two (or more) successive measurements of optical path length at two (or more) discrete laser wavelengths. These independent optical path length measurements are then averaged to create a final data set with reduced error. The proposed measurement sequence is as follows: The instrument measures a first optical thickness profile Z_1 at a first wavelength λ_1, using Eq.(3). Then, the laser is tuned in wavelength an amount $\Delta\lambda$ sufficient to change the relative phase α defined in Eq.(5) by $\pm\pi$. From Eq.(6). The required shift may be calculated from

$$\Delta\lambda = -\lambda^2 / 4nT \tag{9}$$

which is equivalent to an optical frequency shift of

$$\Delta\nu = c/4nT \tag{10}$$

As a rule of thumb, most glasses have an index of n ~ 1.5, for which a 0.1-mm thick substrate would require a $\Delta\nu$ = 500-GHz frequency shift or a $\Delta\lambda$ = 0.7-nm wavelength shift. The instrument now measures a second optical thickness profile Z_2 at a second wavelength $\lambda_2 = \lambda_1 \pm \Delta\lambda$. This measurement will have an equal but opposite error contribution attributable to $\varepsilon_1, \varepsilon_2$. As a final step, the computer averages the two optical thickness profiles:

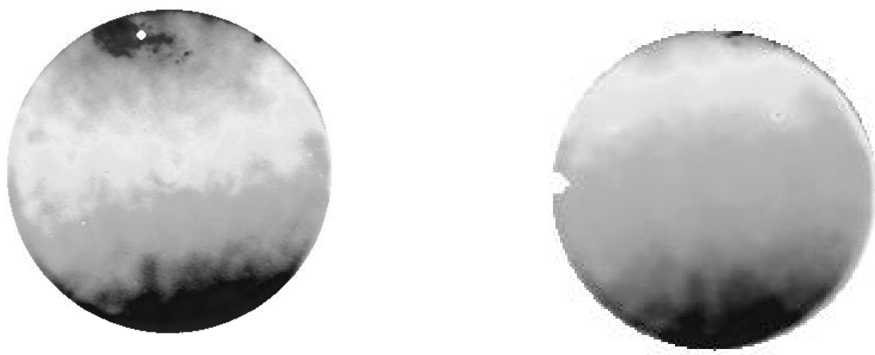
$$Z_{net} = \frac{Z_1 + Z_2}{2} \tag{11}$$

resulting in a final profile Z_{net} with substantially reduced error.

A suitable tunable laser source is the NewFocus model 6304 with a coarse tuning range of 632-637 nm and a wavelength tuning resolution of 0.02 nm. This laser has a continuous fine-tuning range of 70 GHz (0.09 nm) but is easily capable of switching between discrete wavelengths separated by 0.7-nm to invert the error terms on a 0.1-mm thick substrate.

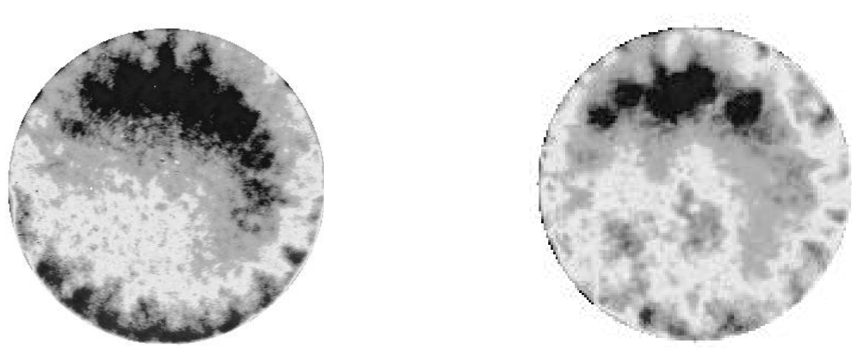
EXPERIMENTAL VALIDATION

I have demonstrated in the lab the proposed technique on a 50-mm diameter, 1-mm thick substrate intended for use in the fabrication of high-precision telecommunications filters, achieving reasonable thickness profiles with a repeatability of the P-V (peak valley) flatness on the order of a nm. The difficulty in measuring these thin substrates means that there are few techniques to validate that the results are accurate. The best solution that I have identified is to use the FTPSI technique operating at an infrared wavelength for which large, continuously tunable laser sources are more readily available.[12] Figures 3 through 5 show comparative results, with a general agreement of a few nm for the two profiles.



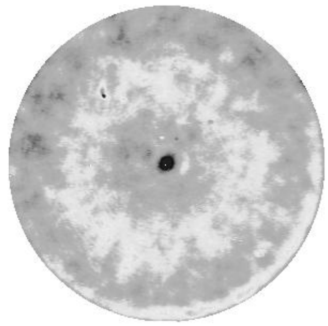
Left: Present technique at 633nm. **Right:** 1550 nm FTPSI.

Figure 3: Optical thickness profile of a glass substrate, showing PV=145 nm of wedge. **Left:** two-step wavelength adjustment technique described in this paper at a nominal 633-nm wavelength; **Right:** independent measurement using Fourier Transform techniques and continuous tuning at 1550nm.

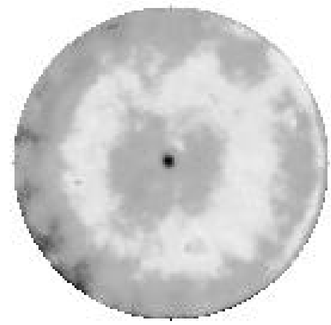


Left: Present technique at 633nm. **Right:** 1550 nm FTPSI.

Figure 2: Optical thickness profile of a substrate having PV=14 nm of flatness error.



Left: Present technique at 633nm.



Right: 1550 nm FTPSI.

Figure 3: Optical thickness profile of part B showing a point defect at the center. PV=21 nm.

CONCLUSION

I show in this paper how one may adapt the familiar laser Fizeau transmission test to the task of high-precision optical thickness profiling by means of a wavelength-adjustable laser. By tuning to two or more successive wavelengths selected to reverse the sign of multiple-reflection error terms, the damaging effect of spurious reflections can be reduced from a few tens of nm to a few nm.

Although this technique overcomes the requirement for a continuously tunable laser for this specific application, I relied upon the more advanced FTPSI technique to for the comparison studies and experimental validation. This suggests that when possible, it is preferable to make this measurement using infrared FTPSI. Nonetheless, if a visible wavelength is a necessity and a suitable wide, continuous-tuning bandwidth source is unavailable, the present technique can be of service.

REFERENCES

1 K. Freischlad, “Large flat panel profiler”, in Proc. Society of Photo-Optical Instrumentation Engineers 2862, Flatness, Roughness, and Discrete Defect Characterization for Computer Disks, Wafers, and Flat Panel Displays, John C. Stover; Ed. 163-171 (1996).

2 P. G. Dewa and A. W. Kulawiec, “Grazing incidence interferometry for measuring transparent plane-parallel plates,” US Patent No. 5,923,425 (Jul. 13, 1999).

3 P. de Groot, "Grating interferometer for metrology of transparent flats" in Vol. **7**, 1996 Technical Digest Series, Optical Fabrication and Testing Workshop, 28-30 (Optical Society of America, Washington, DC, 1996).

4 C. Ai, “Multimode-laser interferometric apparatus for elimination background interference fringes from thin-plate measurements” US Patent No.5,452,088 (Sep. 19, 1995).

5 P. de Groot, "Metrology of transparent flats", in Vol. 13, 1994 Technical Digest Series, Optical Fabrication and Testing Workshop, 160-163 (Optical Society of America, Washington, DC, 1994).

6 K. Okada and J. Tsujiuchi, “Wavelength scanning interferometry for the measurement of both surface shapes and refractive index inhomogeneity,” Proc. Society of Photo-Optical Instrumentation Engineers 1162 Laser interferometry: Quantitative analysis of interferograms, R. J. Pryputniewicz, Ed., 395-401(1989).

7 K. Okada, H. Sakuta, T. Ose and J. Tsujiuchi, “Separate measurements of surface shapes and refractive index inhomogeneity of an optical element using tunable-source phase shifting interferometry,” Appl. Opt. 29(22), 3280-3285 (1990).

8 P. de Groot, “Method and system for profiling objects having multiple reflective surfaces using wavelength-tuning phase-shifting interferometry” US 6,359,692 B1 (Mar. 19, 2002)

9 K. Hibino, B. F. Oreb, and P. S. Fairman, Measurement of surface figure and optical thickness variation of a parallel plate by wavelength scanning interferometry, SPIE 4777 Interferometry XI: Techniques and Analysis, K. Creath and J. Schmit, Eds. Paper 28 (In this volume, 2002)

10 L. Deck, “Simultaneous multiple surface measurements using Fourier-Transform phase shifting interferometry,” Proc Fringe 2001, The 4th International Workshop on Automatic Processing of Fringe Patterns, Wolfgang Osten and Werner Jüptner Eds., Elsevier, 2001. pp. 230-236 (2001). (2001).

11 C. Ai and J. C. Wyant, “Testing an optical window of a small wedge angle: effect of multiple reflections,” Appl. Opt. 32 (Sept. 1, 1993).

12 L.L. Deck, “Absolute distance measurements using FTPSI with tunable IR diodes” SPIE 4778, Interferometry XI: Applications, W. Osten, Ed., Paper 23 (2002).