A wonderful life of holography, interferometry, and optical testing

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James C. Wyant, "A wonderful life of holography, interferometry, and optical testing," Proc. SPIE 10749, Interferometry XIX, 107490P (18 August 2018); doi: 10.1117/12.2324276

Event: SPIE Optical Engineering + Applications, 2018, San Diego, California, United States

A Wonderful Life of Holography, Interferometry, and Optical Testing

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ABSTRACT

The author had a very enjoyable career working with holography, interferometry, and optical testing and during this talk several projects the author worked on during his career will be discussed including 1) Use of computer generated holograms for testing aspheric optics, 2) temporal phase-shifting interferometry, 3) lateral shearing interferometry and adaptive optics, 4) computerized interference microscope, and 5) dynamic (single-shot) phase-shifting interferometry. It will be shown that as technology improves many things that were very difficult to do 30 or 40 years ago are now very simple to do and many ideas that were useless many years ago are now useful.

Keywords: Interferometry, metrology, adaptive optics, optical testing, interference, optical measurements

1. INTRODUCTION

Improved computers, electronics, and software have helped make possible enormous improvements in the measurement of surface shape and surface roughness. These measurement enhancements have in turn made possible enormous improvements in the fabrication of precision optics, hard disk drives, machine tools, and semiconductors. This paper will give a review of some of the computerized optical measurements areas we have been involved with that have led to improvements in the manufacturing of components or systems. For some of the items discussed, at the time the original work was performed the measurement techniques were not very useful because the enabling technology such as plotters, computers, detector arrays, and computing power needed to make useful and accurate measurements were not available, but the concepts were sound and when the supporting technology became available, the measurement techniques became more useful and valuable.

2. COMPUTER GENERATED HOLOGRAMS (CGH)

The ability to use aspheric surfaces in optical systems has greatly improved the quality of optical systems. A major stumbling block in using aspheric surfaces is being able to test the aspheric surfaces. CGHs provide a good method for providing a known reference wavefront for testing aspheres.[1-11] The CGH can be thought of as a binary representation of the interferogram, or hologram, that would be recorded if we were to interfere the aspheric wavefront coming from a perfect aspheric surface with the reference beam. A plotter, such as a laser beam recorder or an e-beam recorder, is used to draw the CGH. Figure 1 shows a simple CGH and Figure 2 shows a typical laser-based Fizeau interferometer with a CGH added to test an aspheric surface. A spherical beam illuminates the CGH and several beams are produced, and one is an aspheric

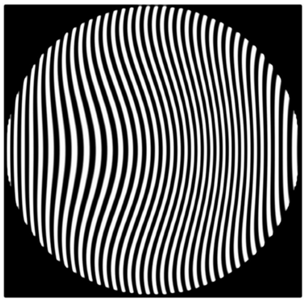


Figure 1. Typical CGH.

Interferometry XIX, edited by Katherine Creath, Jan Burke, Michael B. North Morris, Angela D. Davies,
Proc. of SPIE Vol. 10749, 107490P · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2324276

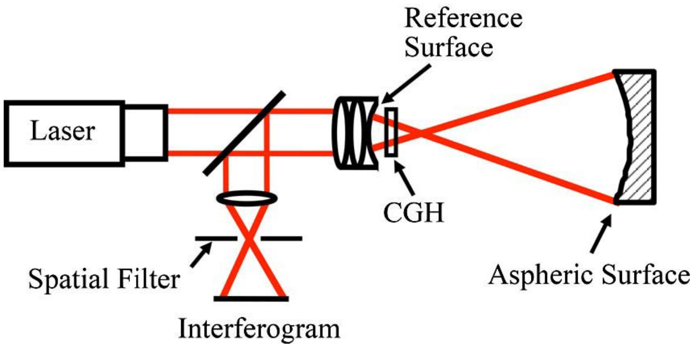


Figure 2. Laser-based Fizeau interferometer with CGH for testing an aspheric surface.

wavefront that has the property that when it reaches the aspheric mirror under test it will match the shape of the aspheric surface if the surface is perfect. The beam is reflected back to the CGH and again several beams are produced, of which one is a spherical wave (if the aspheric surface is perfect) that interferes with the spherical wave reflected off the reference surface. The resulting fringes give the error in the aspheric surface being tested.

The largest potential source of error in the CGH test is the wavefront error resulting from the lines (fringes) making up the CGH being in the wrong location. This error is given by

$$\Delta W(x,y) = \lambda \frac{\varepsilon(x,y)}{S(x,y)}$$

where $\varepsilon(x,y)$ is the fringe position error in the direction perpendicular to the fringes, $S(x,y)$ is the localized fringe error, and λ is the wavelength.

It is especially interesting that when the original work describing the use of CGHs for testing aspheric surfaces was performed, the paper plotters used to make the CGHs were not of sufficient quality to make CGHs for testing anything but the simplest aspheres and the CGH research was only useful for producing papers and talks. Now that high quality electron beam recorders are available, CGHs are truly extremely useful for testing state-of-the-art aspheric surfaces and they are used daily in the manufacturing of sophisticated state-of-the-art optical systems.

3. TEMPORAL PHASE-SHIFTING INTERFEROMETRY (PSI)

Most optical testing interferometers now use phase-shifting techniques because phase-shifting is a highly accurate rapid way of getting the interferogram information into a computer. While the earliest reference to PSI is believed to be 1966[12], the development and demonstration of PSI began in the late 1960's and early 1970's.[13-16] In PSI the phase difference between the interfering beams is either changed in discrete steps (sometimes called phase-stepping interferometry) or it is changed at a constant rate as the detector is read out[15]. It can be shown that by making three or more measurements of the irradiance of the interference pattern as the phase difference is varied, it is possible to accurately determine the phase difference between the two interfering beams. The most commonly used phase shift between consecutive frames of data is 90 degrees because it simplifies the calculations. Generally, more than three phase shifts are used to reduce the requirement for the phase shift being exactly 90 degrees. A four-step algorithm is derived below.

The irradiance of the interference pattern can be written as

$$I(x,y) = I_{dc} + I_{ac}Cos[\phi(x,y) + \alpha(t)]$$

where $\phi(x,y)$ is the phase being measured and $\alpha(t)$ is the phase shift. If four frames of data are taken as the phase changes by 90^{o} between readouts, the irradiance for the four measurements and the measured phase, $\phi(x,y)$, are given by

$$I_1(x,y) = I_{dc} + I_{ac}Cos[\phi(x,y)] \qquad if\ \phi(t) = 0$$

$$I_2(x,y) = I_{dc} - I_{ac}Sin[\phi(x,y)] \qquad if\ \phi(t) = \frac{\pi}{2}$$

$$I_3(x,y) = I_{dc} - I_{ac}Cos[\phi(x,y)] \qquad if\ \phi(t) = \pi$$

$$I_4(x,y) = I_{dc} + I_{ac}Sin[\phi(x,y)] \qquad if\ \phi(t) = \frac{3\pi}{2}$$

$$Tan[\phi(x,y)] = \frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}$$

While this is a very simple equation, it is very powerful and an excellent way of getting interferogram data into a computer.

It is interesting to note that when the original ideas for PSI were developed, PSI was not practical. Solid-state detector arrays were not yet available, computers were large, expensive and not as powerful as you would want, and the required electronics were massive. When we first became involved in the late 1960's and early 1970's, building a phase-shifting interferometer was so expensive that our only source of funding was classified government projects for making active or adaptive optics for satellite reconnaissance systems where cost was not too important. The first system we built had racks of electronics and only 21 discrete detectors, while presently PSI systems using inexpensive personal computers and multi-million-pixel detector arrays are common. In spite of how complicated and crude the first phase-shifting interferometers were, it was possible to demonstrate the adaptive optics correction of atmospheric turbulence[17] and our system worked so well that as soon as it was shown that it worked, the U.S. government classified the work for many years.

4. LATERAL SHEARING INTERFEROMETRY AND ADAPTIVE OPTICS

In an effort to development wavefront sensors for active or adaptive optics for satellite reconnaissance systems we decided to study lateral shear interferometers since they did not require a reference wavefront and the sensitivity can be varied by changing the amount of lateral shear. Lateral shear interferometers give the average value of the slope of the wavefront over the shear distance, rather than the wavefront itself, but since this average slope is essentially the derivative of the wavefront it is easy to calculate the wavefront from the average slope. It must be remembered that we are measuring the slope only in the direction of shear, and since we are generally measuring non-rotationally symmetric wavefronts, we must have at least two measurements with the shear in different, preferably orthogonal, directions. We also must have a shearing interferometer that easily adapts to phase-shifting.

After much thought, we decided to use grating lateral shear interferometers, such as the one shown in Figure 3.[18-22] The interferometer was a two-frequency crossed grating made using holographic techniques. The two frequencies give us two first orders leaving at slightly different angles and hence the lateral shear we want. Increasing the difference between the two line spacings changes the shear and the sensitivity of the test. The crossed-grating gives us shearing interferograms having orthogonal shears, as shown in Figure 4. Moving the gratings sideways gave use a phase difference between the two first orders, so phase-shifting techniques could be used. This phase shift depends only upon the number of grating line periods moved and it is independent of the wavelength of the light source. For example, let one grating frequency be 200 lines/mm and the second one be 220 lines/mm. If the grating is moved with a velocity of 1 mm per second, one first-order will be shifted 200 Hz and the second one will be shifted 220 Hz and the difference is 20 Hz, independent of the wavelength. Note that frequency is the time rate change of phase.

An added feature is that the interferometer is very simple.

In addition to applications in active and adaptive optics, the interferometer found applications in measuring MTF.[23-24] Applications were also found in testing ophthalmic optics[25] because ophthalmic lenses often have a lot of cylinder and it was convenient to have the shear in the direction of the cylinder and perpendicular to the direction of the cylinder. Lateral shear interferometry was also found to have some advantages in testing aspheric surfaces because the amount of shear, and hence the sensitivity of the test, can be selected depending upon the amount of asphericity.[26]

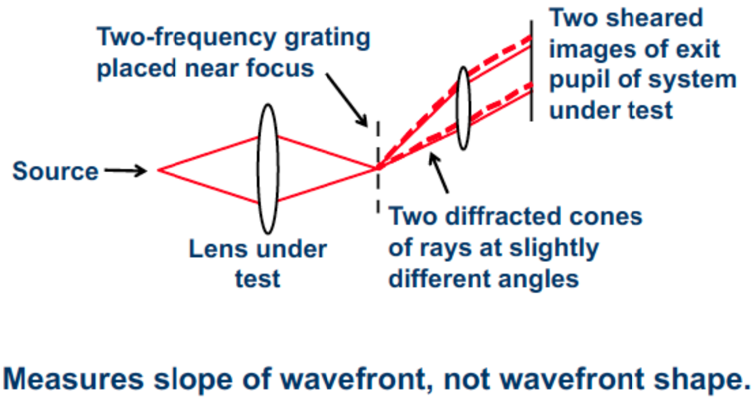


Figure 3. Two-frequency grating lateral shear interferometer.

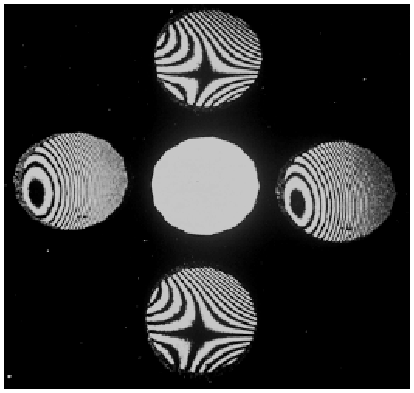


Figure 4. Interferogram obtained using two-frequency grating lateral shear interferometer.

5. COMPUTERIZED INTERFERENCE MICROSCOPE

In the 1980's solid-state detector arrays and personal computers became available, and we decided it made sense to make commercial phase-shifting interferometers, including phase-shifting interference microscopes for the measurement of surface microstructure, and so at the end of 1982 we started a company called WYKO Corporation to design, manufacture and sell phase-shifting interferometers. This section describes a computerized interferometric microscope system[27-29] designed by WYKO for the measurement of surface microstructure where a repeatability of the surface height measurements of less than 0.1 nm could be obtained for smooth surfaces and by using multiple-wavelengths and coherence scanning techniques surfaces having height variations larger than hundreds of microns could be measured to within an accuracy of a few nanometers.

Figure 5 shows a simplified schematic of the instrument using a two-beam Mirau interferometer at the microscope objective. In the figure a tungsten halogen lamp is used as the light source, although LEDs are currently more common. In the phase shifting mode of operation, a spectral filter of 40 nm bandwidth centered at 650 nm is used to increase the coherence length. For the vertical scanning mode of operation described below, the spectral filter is not used. Light reflected from the test surface interferes with light reflected from the reference. The resulting interference pattern is imaged onto the CCD array and the output of the CCD is digitized and read by the computer. The Mirau interferometer is mounted on a piezoelectric transducer (PZT) so that it can be moved vertically. During this movement, the distance from the lens to the reference surface remains fixed. Thus, a phase shift is introduced into one arm of the interferometer. By introducing a phase shift into only one arm while recording the interference pattern that is produced, it is possible to perform either the phase-shifting technique described above, or the vertical scanning coherence sensing technique described below.

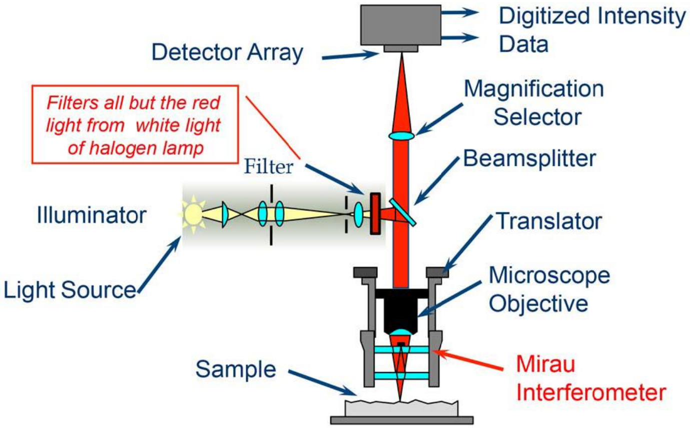


Figure 5. Computerized interference microscope

In the phase-shifting mode of operation the phase is obtained by calculating the arc tangent that gives the phase modulo 2π and hence there may be discontinuities present in the calculated phase. These 2π discontinuities can be removed as long as the slopes on the sample being measured are limited so that the actual phase difference between adjacent pixels is less than π (surface height must change by less than a quarter-wavelength). The dynamic range can be increased by performing the measurement at two or more wavelengths[30-32].

5.1 Two-wavelength interferometry

In two-wavelength interferometry phase measurements are performed at two different wavelengths, and the two-phase measurements are subtracted. Assuming no chromatic aberration is present the result is equivalent to performing a single wavelength at a longer equivalent wavelength given by the product of the two-wavelength divided by the difference. This can be seen as follows.

$$phase\lambda_2 - phase\lambda_1 = 2\pi\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) OPD = \frac{2\pi}{\lambda_{eq}} OPD,\ \ where$$

$$\lambda_{eq} = \frac{\lambda_2 \lambda_1}{Abs[\lambda_2 - \lambda_1]}$$

The maximum surface slope that can be measured is still a quarter-wavelength between adjacent detector points, but now it is a quarter of the equivalent wavelength. Thus, the dynamic range of the measurement is increased by the ratio of the equivalent wavelength to the individual single wavelength.

5.2 Coherence scanning

Often, a better way to increase the dynamic range of an interference microscope is to use coherence scanning.[33-34] In the coherence scanning mode of operation an unfiltered white light source is used. Due to the large spectral bandwidth of the source, the coherence length of the source is short, and good contrast fringes will be obtained only when the two paths of the interferometer are closely matched in length. Thus, if in the interference microscope the path length of the sample arm of the interferometer is varied, the height variations across the sample can be determined by looking at the scan position for each sample point for which the fringe contrast is a maximum.

It is interesting that the ideas of coherence scanning certainly go back to the days of Michelson, but it was not until the 1990’s that the required detectors and computers were available for making a practical commercial system.[34] The early commercial systems used DSPs to perform the required calculations to simultaneously determine the coherence calculations at all detector points. Then personal computers became powerful enough to do the calculations without DSPs and since then as computers became faster and faster it became easier to do the calculations at millions of data points.

6. DYNAMIC (SINGLE-SHOT) PHASE-SHIFTING INTERFEROMETRY

Temporal phase-shifting interferometry is extremely useful for measuring surface shape, but in many situations the environment limits the measurement accuracy and sometimes the environment is sufficiently bad that the measurement cannot be performed. This section describes a technique for reducing effects of vibration by using dynamic (single-shot) phase-shifting interferometry. The single-shot phase-shifting interferometer described is insensitive to vibration and many measurements can be averaged to reduce the effects of air turbulence in the measurement. Also, if surface shape is changing with time, the changes in surface shape can be measured and movies can be made showing how the surface shape changes as a function of time.

The major effect of vibration in temporal phase-shifting interferometry is that the vibration results in incorrect phase changes between consecutive interferograms. Vibration effects can be reduced if all the phase-shifted frames are taken simultaneously and fortunately, there are several ways of obtaining all the phase-shifted frames simultaneously.[35-42] A phase-shifting technique we have worked with that works well with multiple wavelengths, or even white light, involves combining a left-handed circularly polarized beam with a right-handed polarized beam followed by linear polarizers at different angles. For this technique the phase shift between the two interfering beams is nearly independent of wavelength. It can be shown that if these circularly polarized beams are transmitted through a linear polarizer, a phase-shift between the two interfering beams proportional to twice the rotation angle of the polarizer results.[43] See Figure 6a.

Thus, if a phase mask is made of an array of 4 linear wire-grid polarizer elements having their transmission axes at 0, 45, 90, and 135 degrees as shown in Figure 6b, where a polarizer element is placed over each detector element, the mask will produce an array of four 0, $\pi/2$, π, and $3\pi/2$ degrees phase-shifted interferograms. The size of the polarizer elements must be equal to the size of the pixels making up the detector array. Figure 6c shows an SEM photo of the patterned polarizers. It is interesting to note that while it has been known for a long time that rotating a polarizer in a circularly polarized beam changes the phase of the beam, it is only within the past few years that it is possible to produce the required wire-grid polarizer array to work in the visible spectrum.

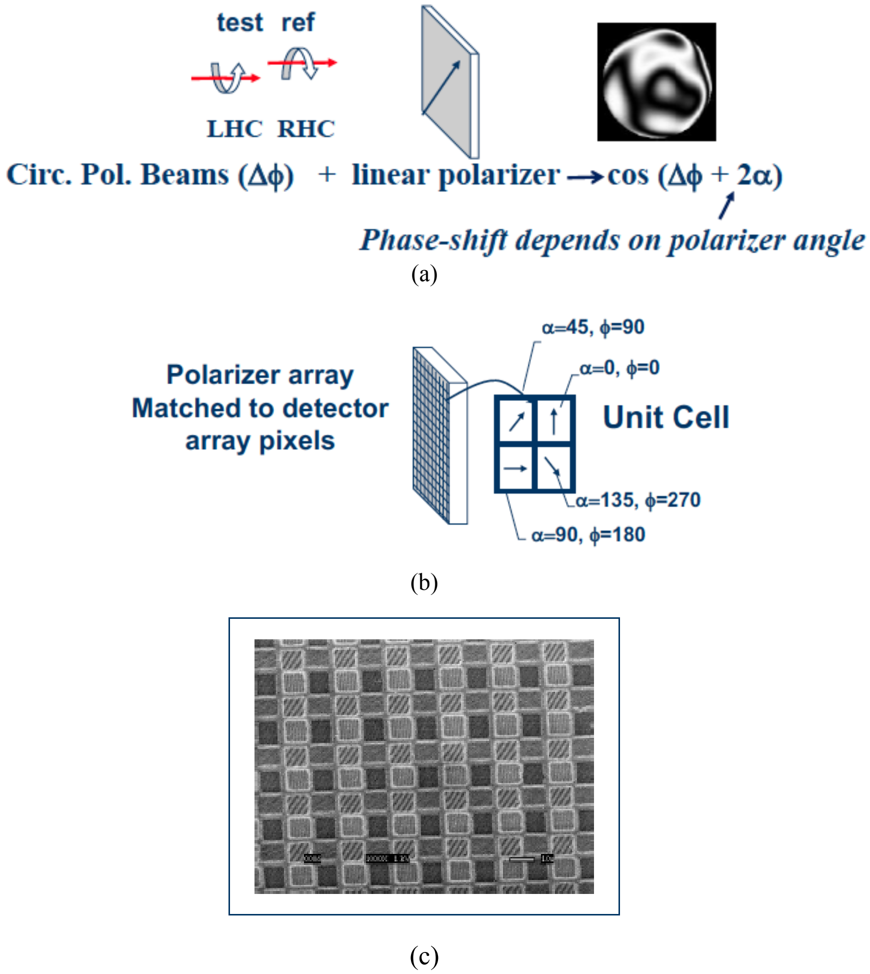


Figure 6. (a) Use polarizer as phase shifter. (b) Array of oriented micropolarizers. (c) SEM of patterned polarizers.

6.1 Single shot Twyman-Green phase-shifting interferometer

It is fairly easy to make a Twyman-Green interferometer using the micropolarizer phase-shifting array and one possible arrangement is shown in Figure 7. The essential characteristics of the two-beam interferometer are that the test and reference beams have orthogonal polarization and the size of the micropolarizer array matches the CCD array. In the figure the polarization beam splitter (PBS) sends one state of polarization to the reference arm and the orthogonal state to the test arm. A quarter-wave plate (QWP) is placed in each arm and after the light passes through each QWP twice the direction of polarization is rotated 90-degrees and the beam that was reflected by the PBS on the first pass will be transmitted on the second pass and the beam that was transmitted on the first pass will be reflected on the second pass. The QWP placed in the output beam converts the orthogonally polarized test and reference beams into left-handed and right-handed circularly polarized beams.

Using this interferometer, it is possible to measure surface shape without any vibration isolation. By averaging several frames of data, the effects of air turbulence can be minimized. If a surface is vibrating it is possible to determine precisely how the surface is vibrating. Movies can be made showing how the shape of the vibrating surface is changing in time.

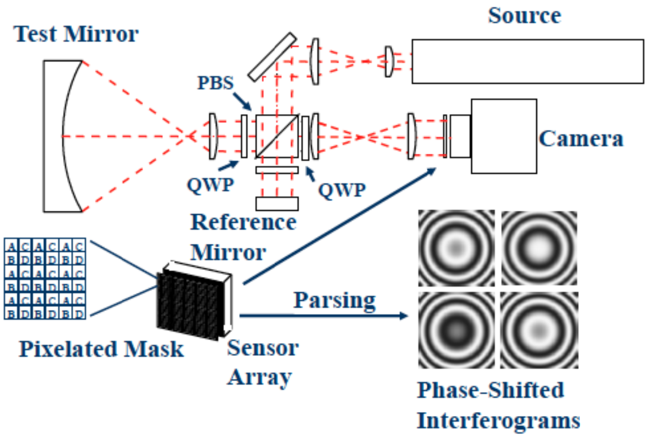


Figure 7. Twyman-Green interferometer with pixelated polarizer array phase-shifting.

6.2 Single shot Fizeau phase-shifting interferometer

A single-shot laser-based Fizeau interferometer is more difficult to construct than a Twyman-Green interferometer because the Fizeau interferometer is more common path and it is hard to obtain a reference and test beam having orthogonal polarization. In principle, a quarter-wave plate can be placed between the test and reference surfaces to rotate the direction of polarization of the test beam by 90 degrees, but in practice it is difficult finding a large quarter-wave plate of acceptable optical quality.

In the interferometer shown in Figure 8 a short coherence light source is used.[44] The source beam consists of two path delayed orthogonally polarized beams. The path difference between the two beams is set equal to the path difference in the Fizeau cavity. The desired interference results from the long path source beam reflected off the reference surface and the short path length source beam reflected off the test surface. All beams are on-axis so off-axis aberrations are not a problem. Since both source beams are reflected off both test and reference surfaces and only the two path-length matched beams give interference, the fringe contrast is reduced, but it is still more than adequate. Since a short coherence light source is used, spurious fringes are greatly reduced.

This interferometer shown in Figure 8 can be used for testing windows having nearly parallel surfaces. If a long coherence source is used spurious fringes are obtained as shown in Figure 9a, however with the short coherence source interferometer spurious fringes are eliminated as shown in Figure 9b and by selecting the proper ΔL in the source, it is possible to look at the fringes for reflection off the first surface or the second surface.

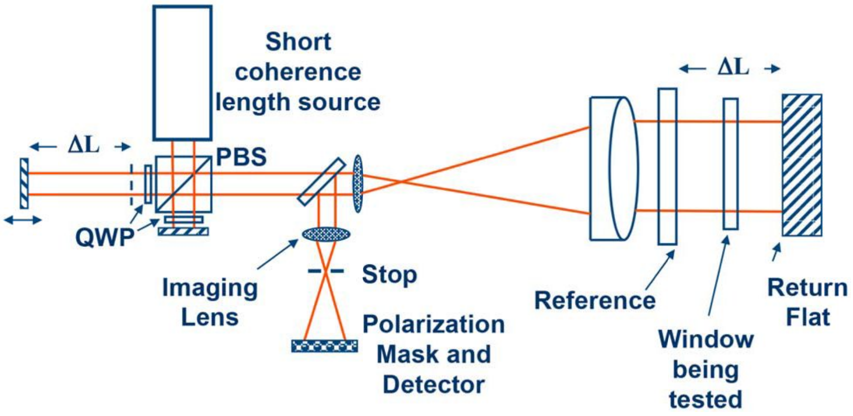
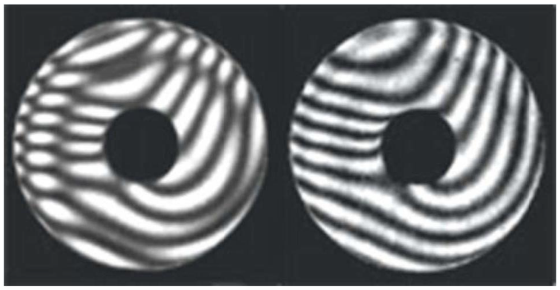


Figure 8. Testing glass sample in transmission or testing each surface in reflection.



(a) Long coherence length source (b) Short coherence length source

Figure 9. Interference fringes obtained testing a thin plate.

A single-shot dynamic interferometer can go a long way in reducing the effects of what is often a large source of error in phase-shifting interferometry, namely vibration. Averaging many frames of data obtained using a single-shot dynamic interferometer can reduce errors due to air turbulence. Averaging data frames in the presence of vibration will average out the double frequency errors common in phase-shifting interferometry and generally more accurate results can be obtained in the presence of vibration than can normally be obtained using conventional temporal phase-shifting interferometry in the absence of vibration. Also, it is possible to measure a vibrating surface to determine precisely how the surface is vibrating and movies can be made showing how the vibrating surface shape changes. Once a person works with a simultaneous dynamic phase-shifting interferometer, it is hard to go back to working with a temporal phase-shifting interferometer.

7. FINAL COMMENTS

This paper, which is a shortened version of reference 45, has given some examples of where the addition of electronics, computers, and software to well-known interferometry techniques has provided enormous improvements in optical metrology. When the initial work was performed for most of the examples, the techniques were not real useful because the necessary enabling technology was not yet available, but the concepts were sound and when the supporting technology became available the measurement techniques became useful and valuable. This is true in all areas of research, and just because a particular concept is not currently useful, it does not mean that it will never be useful.

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