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Amazing scatterplate interferometer

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ABSTRACT

The scatterplate interferometer is an amazing instrument invented by James M. Burch in 1953 for testing optical components and it is especially good for testing concave mirrors. This interferometer requires no high-quality optical components and it generates its own reference wavefront without having a reference surface. The light source does not have to be a point source or monochromatic - almost any light source will work. The path lengths of the two interferometer paths are automatically matched and, regardless of the reflectance of the test mirror, the light intensities of the two interfering beams are matched. The interferometer is not very sensitive to vibration and it is inexpensive to build. There are several ways to use phase-shifting techniques with the interferometer. This talk will describe and explain the properties of the amazing scatterplate interferometer.

Keywords: Interferometry, interferometers, interference, optical testing, metrology, measurements, phase-shifting

1. INTRODUCTION

While the theory and operation of the scatterplate interferometer are well known, for some reason they are not widely known. To aid in understanding how a scatterplate interferometer works, it is advantageous to think about a related experiment we might perform in our home using light scattered by our bathroom mirror to produce white light interference fringes.

The back surface of your bathroom mirror is highly reflecting. For this experiment we need to put some powder on the front surface of the mirror. Stand back a meter or so from the mirror and put a small bright light source, such as a cell phone flashlight, close to your eye and illuminate the mirror. You should see white light interference fringes. Move your head around relative to the light source and the spacing and orientation of the fringes will change. While this may seem like magic, it is easy to see how it works. Some of the light is scattered by the powder on the first surface and reflected by the second surface of the mirror and some of the light is reflected by the second surface of the mirror and then scattered by the dust on the first surface as shown in Figure 1. The scattered-reflected beam and the reflected-scattered beams interfere to give white-light fringes. The path difference between the two interfering beams depends on the angle of scattering and is zero when this angle is zero. Since the mirror surface is flat, the emergent rays are parallel and the resulting interference fringes are seen at infinity. In 1953 Burch[1] used this phenomenon to make a remarkably simple interferometer for testing optical systems.

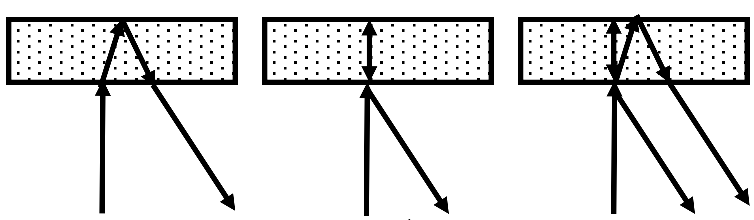

Figure 1. a) scattered first surface, reflected second surface, b) reflected second surface, scattered first surface, c) scattered-reflected and reflected-scattered beams which can interfere to produce white light fringes.

2. ORIGINAL BURCH SCATTERPLATE INTERFEROMETER

For the original scatterplate interferometer shown in Figure 2 for testing a concave mirror, Burch used partially scattering surfaces produced by lightly grinding one surface of plate glass so some of the original surface is left between

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the pits.[1-4] He then made two replicas, scatterplate S1 and scatterplate S2, of the surface by casting a film of collodion or other plastic onto the surface or heating the glass and then pressing it against some thermoplastic material. In the interferometer a lens focuses light from a small source onto the mirror being tested. Scatterplate S1 is located near the center of curvature of the mirror being tested. Scatterplate S2, which is identical to S1, is placed at the image of S1. S2 is oriented so each point of S1 is imaged onto the corresponding point of S2. The light scattered by S1 will cover the entire surface of mirror being tested, while the light not scattered will illuminate only a small portion of the mirror being tested. Part of the light that was scattered by the first scatterplate will not be scattered by the second scatterplate (scattered-direct) and part will be scattered again (scattered-scattered). Part of the light that is not scattered by the first scatterplate will be scattered by the second scatterplate (direct-scattered) and part of the light that was not scattered by the first scatterplate will not be scattered by the second scatterplate (direct-direct). Thus, the light transmitted through the second scatterplate can be divided into four categories: (1) direct-direct, (2) direct-scattered, (3) scattered-direct, and (4) scattered-scattered. The direct-direct light will produce a bright or hot spot in the interferogram, while the scattered-scattered beam will reduce the fringe contrast. The scattered-direct beam has information in it about the aberrations in the mirror, while the direct-scattered beam illuminated only a small portion of the mirror so aberrations in the mirror do not change this beam. The scattered-direct beam serves as the test beam and the direct-scattered beam serves as the reference beam. The interferogram resulting from the scattered-direct beam and the direct-scattered beam shows the same information as a Twyman-Green interferogram. Moving one of the scatterplates sideways produces tilt fringes and moving one of the scatterplates longitudinally produces defocus fringes. All of this will be described in more detail below when we discuss the second generation scatterplate interferometer configuration.

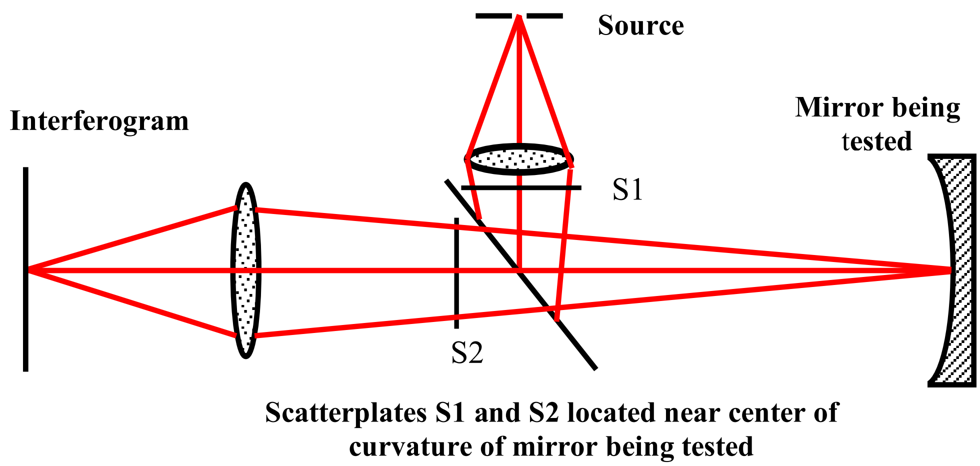


Figure 2. Original Burch scatterplate interferometer.

It is important to note that the two scatterplates must be identical because each scatterplate introduces a random phase variation in the beam and, when the scattered-direct and the direct-scattered beams interfere, the random phase variations introduced by the two scatterplates must be identical so the random phase cancels out and what we have left is the phase variations introduced by the errors in the mirror being tested.

3. SECOND GENERATION SCATTERPLATE INTERFEROMETER

While the original Burch scatterplate interferometer had two identical scatterplates, most current scatterplate interferometers have a single scatterplate placed near the center of curvature of the concave mirror being tested as shown in Figure 3.[5-11] Part of the light illuminating the scatterplate will pass unscattered to focus directly on the mirror surface, while part of the light will be scattered uniformly over the mirror surface. The mirror will reimage the scatterplate back on itself--inverted, of course, which means the scatterplate must have inversion symmetry since the random phase variation introduced into the scattered-direct beam must be the same as the random phase variation introduced into the direct-scattered beam so the random phase cancels out and what we have left is the phase variations introduced by the errors in the mirror being tested.

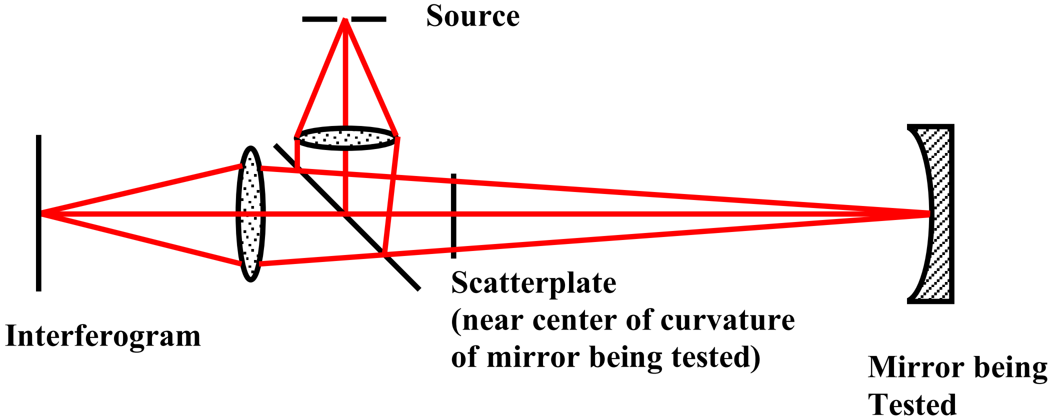
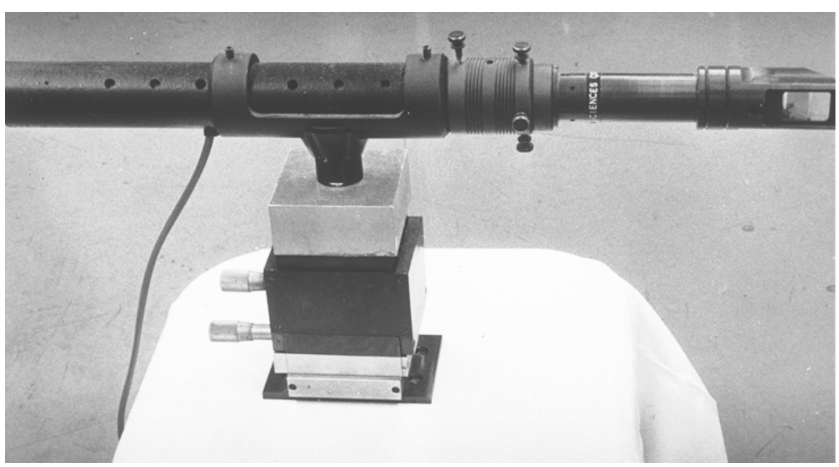


Figure 3. Scatterplate interferometer for testing concave mirror.

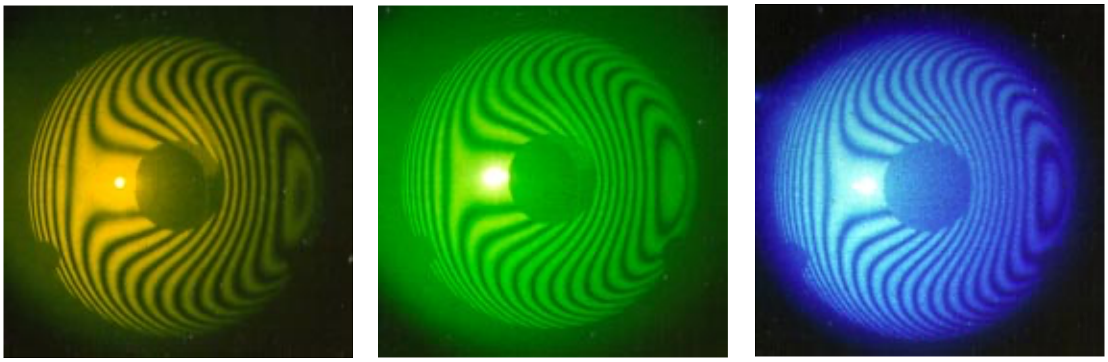
Figure 4 shows a photo of a scatterplate interferometer where the light source is a helium neon laser. The scatterplate can be seen on the right side of the figure. The interferometer is mounted on an XYZ stage so the scatterplate can be carefully placed near the center of curvature of the concave mirror under test.



4.

Figure 4. Scatterplate Interferometer using HeNe laser as the light source.

Figure 5 shows three scatterplate interferograms obtained testing a concave parabolic mirror at center of curvature.



568.2 nm 520.8 nm 476.2 nm

Figure 5. Three scatterplate interferograms obtained testing the same mirror at different wavelengths.

4.1 Making the scatterplate

The most critical part of the instrument is the scatterplate itself, which can easily be made. The basic procedure for making a scatterplate is to expose photoresist to a speckle pattern produced by illuminating a piece of ground glass with a laser beam. Since the scatterplate must have inversion symmetry, two superimposed exposures to the speckle pattern must be made, where the plate is rotated 180º between the exposures. The error in this 180-degree angle rotation should not be larger than about one arcsecond. To ensure that the scatterplate illuminates the surface under test as uniformly as possible, during the making of the scatterplate the solid angle subtended by the illuminated piece of ground glass, as viewed from the photoresist plate, should be at least as large as the solid angle of the surface under test, as viewed from the scatterplate during the test. Note that this solid angle determines the size of the structure making up the scatterplate. After development, the photoresist plate should be processed to yield a phase scatterplate. The exposure and processing should be controlled so the scatterplate scatters 10 to 20% of the incident light. If the scatterplate scatters too much, the scattered-scattered beam will be too bright and the fringe contrast will be low. If it scatters too little, the direct-direct beam (hot spot) will be too bright.

A second approach for making a scatterplate is to calculate on the computer what the scatterplate should look like and have an electron beam recorder print out the scatterplate.

Figure 6 shows a high magnification photograph of a scatterplate. This scatterplate was made for operation at a wavelength of 10.6 microns so the detail making up the scatterplate is large enough to easily observe through a microscope.[12] Note the inversion symmetry of the structure making up the scatterplate. The structure size making up the scatterplate controls the angle the light is scattered.

The scatterplate is typically about a cm in diameter. If the scatterplate is too small, the resolution of the image of the mirror will be low and if the size is too large, the light scattered from near the edges of the scatterplate will result in an aberration different from the light scattered near the center of the scatterplate. It is convenient having a cross hair at the center of inversion symmetry, so it is easy to see if the scatterplate is imaged back on itself without much lateral misalignment. The interferometer generally includes a small magnifier focused on the center of the scatterplate to aid in determining if for the second pass of light through the scatterplate, the image of the crosshair from the first pass falls back on the scatterplate crosshair. As shown below, lateral misalignment will introduce tilt fringes and if there are too many tilt fringes, they will be hard to see.

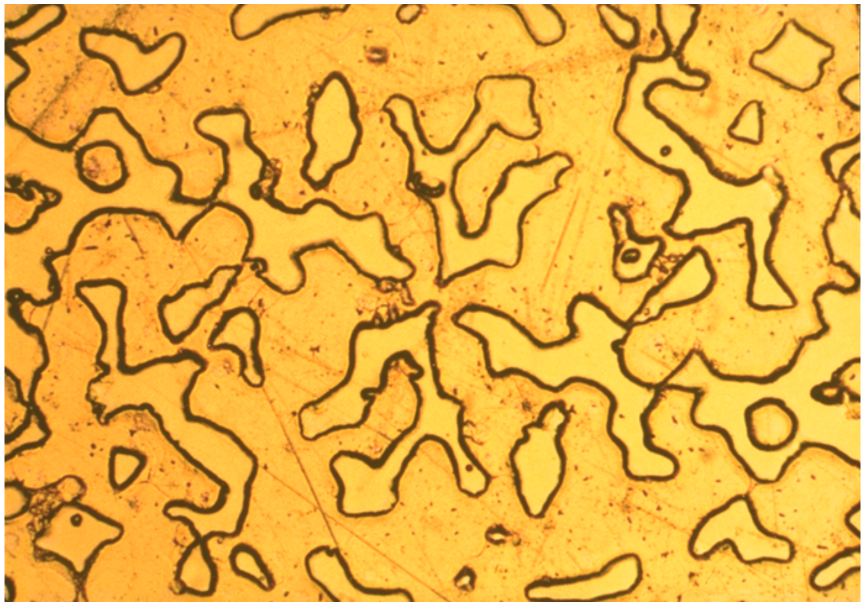


Figure 6. High magnification photograph of a scatterplate. Note the inversion (flip) symmetry.

4.2 Common path features of the scatterplate interferometer

The scatterplate interferometer shown in Figure 3 is common path in the sense that the test and reference beams travel nearly the same paths. This means that errors in the two lenses, beamsplitter, and scatterplate substrate will introduce the same errors in both the test and reference beams and will cancel out. Thus, the interferometer does not require high quality optics.

Furthermore, because of the common path property, the interferometer is much less sensitive to vibrations than a non-common path interferometer such as a Twyman-Green interferometer. Since both the reference and the test beams reflect off the mirror under test, the interferometer is very insensitive to longitudinal vibration and for most situations this interferometer does not need a vibration isolation table to work well. This vibration insensitivity is a wonderful feature of the scatterplate interferometer.

4.3 Light source requirements

Another great feature of the scatterplate interferometer is that the source requirements, bandwidth and size, are not stringent. At the location of the hot spot, that is the image of the source and focus of the direct-direct beam, the paths are exactly matched, and we have a bright fringe. For this fringe that passes through the hot spot the optical path difference between the reference and test beam is zero. For the next bright fringe of tilt fringes, the optical path difference, OPD, between the two interfering beams is one wave and for the next bright fringe the OPD is 2 waves, and so forth. It we are using a white-light source, the fringes for the different wavelengths separate as we move away from the hot spot. White light fringes are beautiful and the scatterplate interferometer is a great way to see these beautiful white light fringes. The allowable bandwidth of the source depends upon how many fringes we have in the interferogram.

How large can the source be? If the source is an extended spatially incoherent source, we can think of the source as being made up of a collection of point sources, where each point source produces its own set of interference fringes. For a given point source the zero-order fringe passes through the image of the point source and the final fringe intensity is a convolution of the source distribution with the fringe pattern for a point source. As a rule of thumb, the fringe contrast is zero when the imaged source size approaches the fringe spacing.

Beautiful speckle free colorful interferograms can be obtained using an extended white light source as the light source for a scatterplate interferometer, however, generally a laser source is used because it is so easy to use and the source is so bright.

4.4 Introducing tilt and defocus

If a perfect spherical mirror is being tested and the scatterplate is located at the center of curvature of the mirror such that the scatterplate is imaged back onto itself, a single fringe is obtained. If the scatterplate is shifted sideways, the image of the scatterplate will move in the opposite direction. The image of a scatter point from the first pass through the scatterplate and the corresponding scatter point on the other side of the scatterplate will be separated twice the distance the scatterplate was moved, as shown in Figure 7a. Hence, lateral displacement of the scatterplate introduces tilt fringes in the interferogram.

Likewise, if the scatterplate is moved longitudinally, the image of the scatterplate will move in the opposite direction. The image of a scatter point from the first pass through the scatterplate and the corresponding scatter point on the other side of the scatterplate will be separated longitudinally twice the distance the scatterplate was moved, as shown in Figure 7b. Hence, longitudinal displacement of the scatterplate introduces defocus fringes in the interferogram.

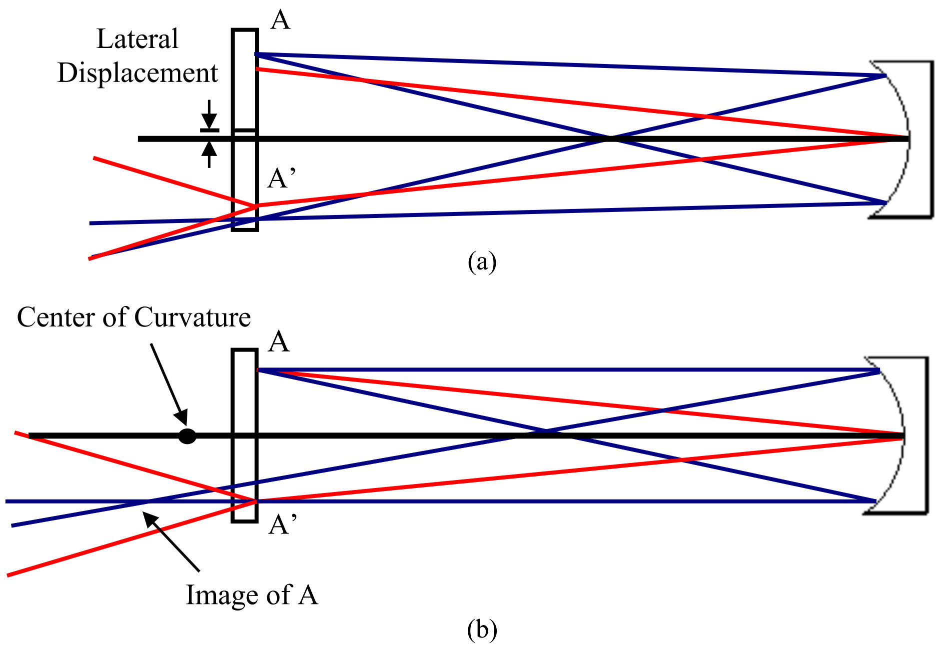


Figure 7. Introducing tilt (lateral displacement) and defocus (longitudinal displacement).

Figure 8 shows three typical interferograms obtained using a scatterplate interferometer. The scatterplate interferometer was moved slightly between recording the three interferograms to change the amount of tilt and defocus.

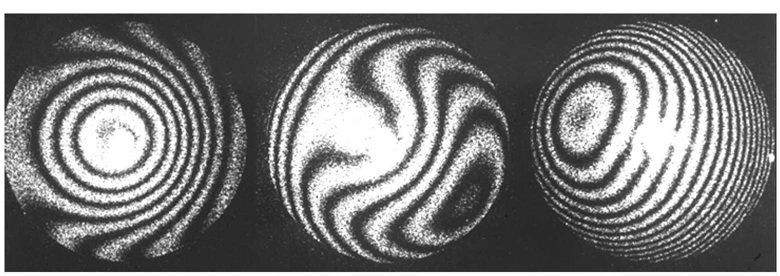


Figure 8. Scatterplate interferograms of parabolic mirror.

4.5 Conservation of energy

By adding the energy produced in the interferograms and absorbed by the interferometer itself, it must be possible to prove energy conservation in any interferometer. This calculation is relatively simple for two port interferometers such as the Twyman-Green and Mach-Zehnder. If non-absorbing beam splitters are used, primary and complementary fringe patterns are produced such that when a dark fringe appears in one port a bright fringe appears in the other. The sum of the energy in the two fringe patterns remains a constant. If absorbing beam splitters are used such as thin film aluminum, the two fringe patterns are not necessarily complementary, however, it can be shown that if the energy absorbed by the beam splitter is included in the calculation, the total energy again remains constant.

How is energy conserved in a scatterplate interferometer? If we have a dark fringe where has the energy gone? The answer depends upon whether the interferometer has a density scatterplate or a phase scatterplate.[13] The trade off in energy, as a dark fringe appears, occurs between the hotspot and the signal in a phase scatterplate. For the density scatterplate, the tradeoff is between the plate absorption and the signal.

5. PHASE-SHIFTING SCATTERPLATE INTERFEROMETER

Phase-shifting interferometry provides a great way of getting interferometric data into the computer so the data can be properly analyzed, and almost all interferometric optical testing is now performed using phase-shifting techniques. A great advantage of the scatterplate interferometer is that it is a common path interferometer so it is less sensitive to vibration and lower quality optical components can be used, thus reducing the cost of the interferometer. Unfortunately, the same feature that makes common-path interferometers desirable also makes phase shifting complicated. Since the test and reference beams traverse the same optical path, it is difficult to separate them for phase shifting. It is no longer feasible to place a phase-shifter in just one beam. The challenge then is to produce a variable phase difference between the test and reference beams.

In the case of the scatterplate interferometer there are a few approaches that work. One common technique is to place a small quarter-wave plate near the test surface that rotates only the incident linear polarization of the reference beam by 90^{o}.[14-15] With orthogonal polarizations in the test and reference beams, the interferometer is phase shifted using an electro-optic light modulator. It is necessary to correct for the phase error introduced by the quarter-wave plate.

Another approach, which does not require auxiliary optics to be placed near the test surface, is to use a birefringent scatterplate to separate the test and reference beams as shown in Figure 9.[16-18]

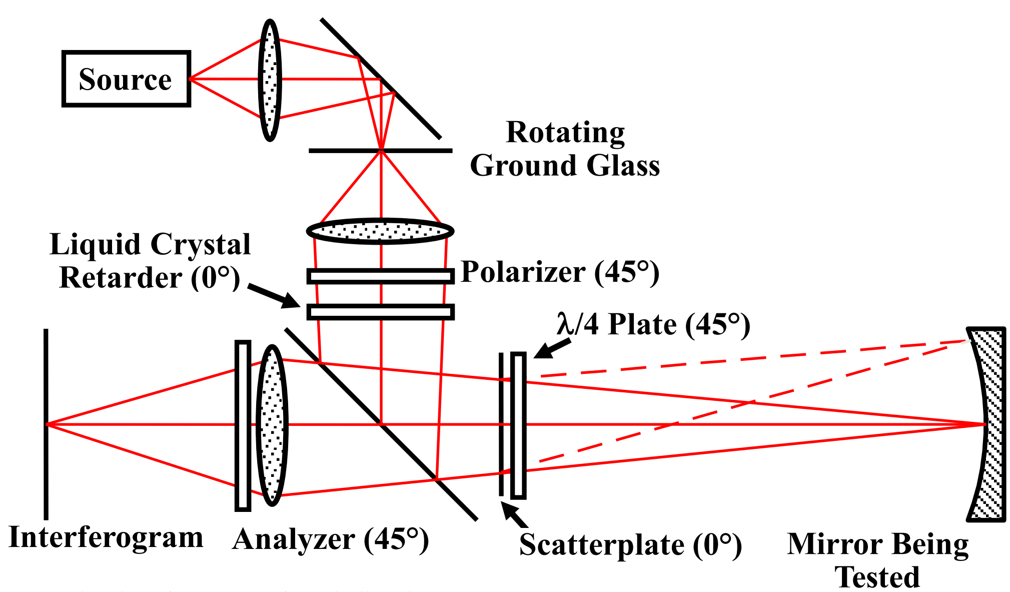


Figure 9. Scatterplate interferograms of parabolic mirror.

The birefringent scatterplate selectively scatters one polarization component of the incident beam while allowing the orthogonal component of polarization to pass directly through. The scatterplate can be made of calcite, where the appropriate pattern with inversion symmetry is etched into a calcite retarder using a chemical etching process. An index matching oil chosen to match the ordinary index of the crystal is then pressed between the calcite and a glass slide. A spectrally narrow source (laser) is used so the chromatic variations of the polarization elements have a minimal effect. The first polarizer passes linearly polarized light at 45 degrees with respect to the optic axis of the birefringent scatterplate, so half the beam will see the ordinary index of the crystal and not scatter because of the index-matching oil. The other half of the beam will partially scatter due to the index mismatch between the extraordinary index and the oil. The quarter-wave plate at 45 degrees exchanges the two beams so that the unscattered reference beam scatters in the birefringent scatterplate, while the scattered test beam is unscattered on the second pass through the scatterplate. Note, that if there is no unwanted scattering of the direct beams, there will be no background irradiance term. If all the light scatters for the scattered beam, the hotspot is eliminated. An analyzer at 45 degrees is needed to combine the beams so they interfere. A liquid crystal retarder at 0 degrees before the beamsplitter introduces a variable phase shift between the two beams.

6. A SIMPLE, BUT NOT TOO USEFUL, SCATTERPLATE INTERFEROMETER

The scatterplate interferometer shown in Figure 10 uses a piece of ground glass as the scatterplate and it is extremely easy to setup and get beautiful interference fringes, but the fringes obtained are not very useful.[19] The problem is that the beam is flipped over for the second reflection off the mirror under test, so all the odd aberrations are missing. This version of the scatterplate is presented, even though it is not very useful, because it is a lot of fun to play with. Try it!

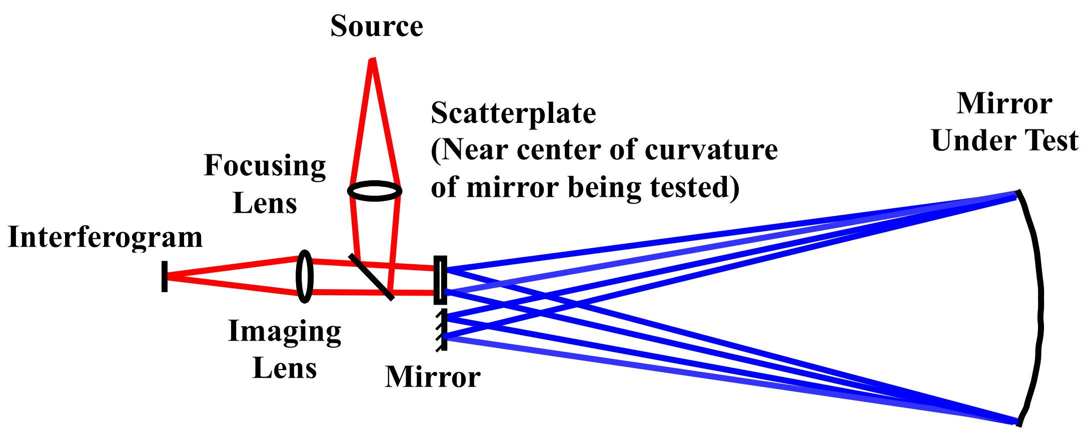


Figure 10. Scatterplate interferometer that uses a piece of ground glass as the scatterplate.

7. FINAL COMMENTS

The advantages of the scatterplate interferometer are that the instrument is simple and inexpensive, requires no accessory optics, and because the interferometer has a common path, it is less sensitive to vibration and turbulence. If an incoherent source is used as the light source, the coherent noise (extraneous fringes), normally associated with using a laser as the light source, is absent. Beautiful white light fringes can be obtained. Small, almost insignificant, disadvantages are that the hot spot can cause a loss of fringes for a small portion of the interferogram and the twice-scattered beam will cause the interferogram to have somewhat lower contrast than can be obtained using a Twyman Green interferometer. For reasons I do not understand, the scatterplate interferometer is almost never used and it is often forgotten about. This is a shame, because it is a wonderful instrument. In fact, it is my favorite optical instrument.

ACKNOWLEDGMENTS

Roland Shack showed me my first scatterplate interferometer during my first visit to the University of Arizona in 1971. Over the years he and I discussed the scatterplate interferometer many times. I had two students, Larry Rubin and Michael North-Morris, who did PhD dissertations on scatterplate interferometers for me and answered the many questions I had on the scatterplate interferometer. A third former student, John Hayes, did not do his dissertation on the scatterplate interferometer, but he and I have discussed it many times and he loves the instrument almost as much as I do.

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