Interferometric Optical Metrology

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Lasers have made truly revolutionary changes in optical metrology. The laser's small source size and narrow linewidth made it so much easier to obtain good contrast interference fringes that applications of interferometric optical metrology have increased immensely during the 50 years since the laser was first developed. Single-mode frequency-stabilized lasers provided a standard for dimensional metrology, while ultra-short pulsed lasers have enabled high-resolution range finding.

The laser has greatly enhanced the testing of optical components and systems. Before the laser, the use of interferometry in optical testing was limited because either the interferometer paths had to be matched or the source size had to be very small to have good spatial coherence, and the filters needed to reduce spectral width left very little light for measurements. Once the laser was introduced, Bob Hopkins from the Institute of Optics at the University of Rochester was quick to realize how much laser light could improve the testing of optical components [1], and he encouraged other researchers to design laser source optical interferometers [2–6]. By 1967 lasers had become common in optical testing [7,8]. Figure 1 shows a laser unequal path interferometer (LUPI) designed by John Buccini and manufactured by Itek in the late 1960s and early 1970s.

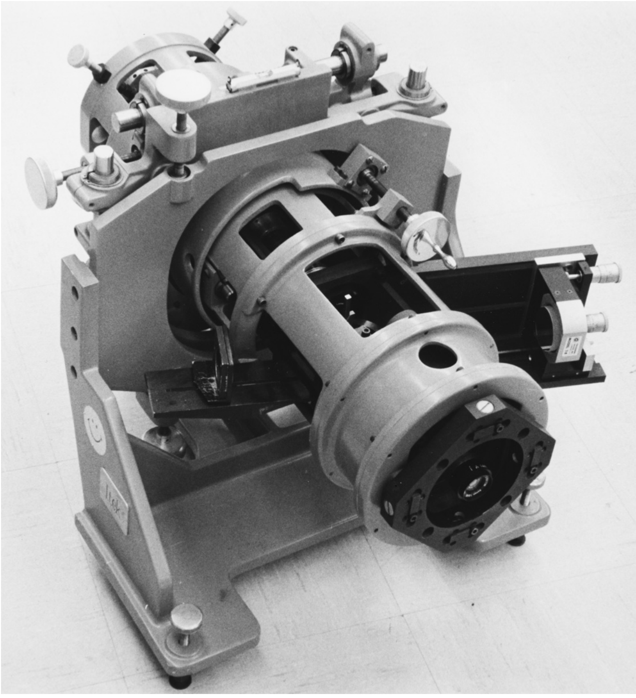
Abe Offner from Perkin Elmer was quick to realize that adding null correctors to laser interferometers would allow measurements of optical components with aspheric surfaces [9]. Null correctors are a combination of lenses and mirrors having spherical surfaces, but when used in the proper way they produce an aspheric wavefront that matches the surface of an aspheric optic, producing interferograms with straight equally spaced fringes when the tested aspheric surface is perfect. Unfortunately, that use of null correctors received horrible publicity after initial orbital tests of the Hubble Space Telescope showed its optics could not be brought to the expected sharp focus. Analysis of the flawed images showed that the primary mirror had an incorrect shape. A commission headed by Lew Allen, director of the Jet Propulsion Laboratory, determined that the null corrector used to test the primary mirror had been assembled incorrectly—one lens was 1.3 mm from its proper position [10]. That caused the null corrector to produce an incorrect aspheric wavefront, so using it to test the primary mirror led to fabricating the mirror with the wrong shape. In correcting the error, the cost was more than a billion dollars to design and fabricate additional optics and install them on the Hubble telescope from the space shuttle.

Heterodyne and Homodyne Interferometry

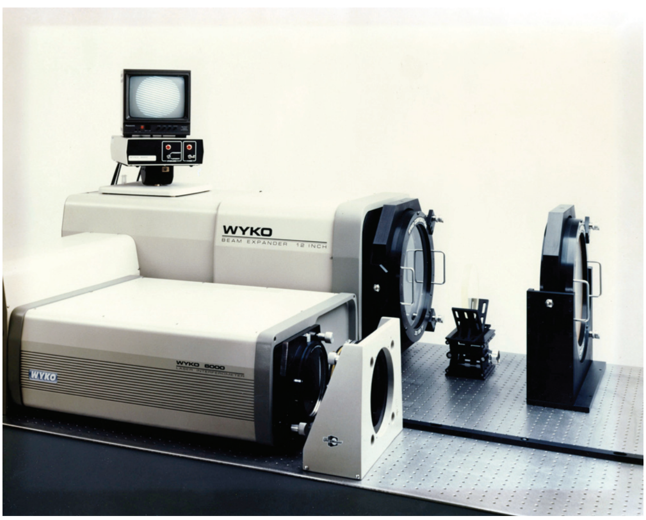
Heterodyne interferometry using the beat signal between two different laser frequencies permits the measurement of changes in distances or variations of surface height in the nanometer or angstrom range. The two frequencies are commonly obtained from a Zeeman split laser [11], rotating polarization components [12], or Bragg cells [13].

Homodyne interferometry using either a phase-shifting [14,15] or spatial-carrier [16] technique is now widely used to test optics. In phase-shifting interferometry three or more interferograms are captured where the phase difference between the two interfering beams changes by some amount, typically 90 degrees, between consecutive interferograms. From these three or more interferograms the phase difference between the two interfering beams can be determined. In spatial-carrier interferometry a large amount of tilt is introduced between the two interfering beams, and the resulting interferogram is sampled such that three or more measurements are made per fringe.

Adding a computer to an interferometer creates a great metrology tool for use in manufacturing many types of components including optics, hard disk drives, machined parts, and semiconductors [17]. Figure 2 shows a phase-shifting laser-based Fizeau interferometer manufactured by the WYKO Corporation in the late 1980s, and Fig. 3 shows a phase-shifting interference microscope also manufactured by WYKO in the mid-1980s for measuring surface microstructure.



▲ **Fig. 1.** Laser unequal path Twyman–Green interferometer, often called a LUPI (1970).



▲ **Fig. 2.** Laser-based phase-shifting Fizeau interferometer having both a 6-in. and a 12-in. aperture (late 1980s).

The great feature of phase-shifting interferometry is that it can measure distances to nanometer or even angstrom accuracy, but it only measures phase over a range of 2π and wraps if the phase varies by more than 2π. The phase can be unwrapped if it varies slowly, but not if the surface has large steps or discontinuities. The problem arises from the monochromaticity of the laser light used in the measurement. One way to get around the unwrapping problem is to measure a surface at two or more wavelengths and observe how the phase changes when the wavelength is changed [18]. A second approach is to observe how the phase changes as the frequency changes when using a tunable laser source [19]. A third approach is to reduce temporal coherence of the source and observe how fringe visibility changes as the path difference between the two interfering beams changes [20]. It is interesting that the use of a low-coherence-length source, essentially white light, is the same approach Michelson used more than a hundred years ago. The modern addition of electronics, computers, and software make the technique much more powerful and useful for a wider variety of applications.

Holographic Interferometry and Speckle Metrology

The laser allowed optical interferometry to expand to include interference of random optical fields scattered from diffuse surfaces. For example, the coherence of laser light is essential in holographic interferometry [21] and speckle metrology [22]. One example is using holographic interferometry to measure deformation, first discovered and described by Karl Stetson [23]. First a hologram is recorded of a three-dimensional (3D) object, and then the object is deformed so light from the reconstructed hologram can interfere with the optical field from the deformed object to yield interference fringes showing how the object was deformed. One particularly good application of such holographic nondestructive testing is the testing of automotive and aircraft tires pioneered by Gordon Brown [24]. Changing tire pressure slightly between two holographic exposures causes small bulges in weak areas that show up very clearly in the resulting holographic interferogram.

▲ **Fig. 3.** Phase-shifting interference microscope for measuring surface microstructure (1985).

Time-averaged holography effectively measures surface vibration [25]. A hologram is made of a vibrating surface over a time long compared with the vibration period. Interference fringes are recorded from the nodes of the vibration but are washed out by movement of the vibrating part of the surface. The result is a fringe contour map showing the location of the vibration nodes.

Two-wavelength holography can be used to contour surfaces [26]. One technique starts by recording a hologram of a surface using a wavelength, λ_1. Then both the surface being contoured and the hologram are illuminated with a second wavelength, λ_2, and the optical wavefront reconstructed by the hologram is interfered with the optical wavefront from the object being illuminated with wavelength λ_2. The resulting interference pattern gives the shape of the surface being measured at a synthetic wavelength, λeq given by $\lambda_1 \lambda_2/(\lambda_1-\lambda_2)$. Diffuse surfaces can be contoured as long as λeq is large compared with surface roughness.

Solid-state detectors now have sufficient resolution to record a hologram on a high-resolution image detector, and a computer can reconstruct the optical field [27]. Phase-shifting interferometric holography can measure deformation and vibrations and can contour complex surfaces by using multiple wavelengths.

Computer generated holograms (CGHs), invented by Adolf Lohmann [28], have become common in the laser interferometric testing of aspheric surfaces [29]. Aspheric surfaces have become common in optical systems because they can produce better images with fewer optical elements than spherical surfaces. A computer can calculate a CGH to provide a reference wavefront, and an electron-beam recorder can fabricate the CHG. Then the CGH is put into the laser interferometer to produce the required reference wavefront. The use of CGHs with laser interferometers has helped to greatly improve modern optical systems.

Speckle photography and the interferometer are closely related to holographic interferometry. Illuminating a rough surface with a laser beam produces a grainy distribution of light, resulting from coherent superposition of the random optical fields scattered by the rough surface. Originally considered a nuisance, this speckle pattern was later recognized as containing information about the light-scattering surface. For example, the contrast of the speckles can give information about the roughness of the surface [30]. Speckle contrast as a function of position can give vibration information [31]. Deforming the surface changes the speckle pattern by changing optical pathlengths, and comparing speckle patterns before and after deformation can determine distribution of the deformation [32].

Speckle metrology has become more and more useful as high-resolution image sensors and software analysis programs have improved.

Improved Measurement Capability

Lasers make it easy to get interference fringes, but sometimes they can generate fringes from stray beams in an interferometric setup. For example, surface reflections during the transmission measurement of a glass plate can produce spurious interference fringes that greatly reduce accuracy. Using a low-temporal-coherence source and matching the two arms of the interferometer can get around this, but matching the lengths of the two arms can be difficult and reduce the usefulness of the interferometer. A better approach is to add an optical delay line that splits the source beam into two components and allows a controllable path difference between the two beams. That eliminates both the spurious interference fringes and the need to match the test and reference beam pathlengths [33].

The environment affects phase-shifting interferometry, and in many cases, especially in manufacturing situations or testing large telescope optics, it can limit accuracy or sometimes even prevent measurements. The problem is that in conventional phase-shifting interferometry three or more interferograms are obtained at different times for which the phase difference between the two interfering beams changes by 90 degrees between consecutive interferograms. Vibrations can cause incorrect phase changes between consecutive interferograms. However, vibration effects can be reduced by taking all of the phase-shifted frames simultaneously, and now high-resolution image sensors offer several ways to obtain all of the phase-shifted frames simultaneously. One technique that works very well is to have the test and reference beams have orthogonal circular polarizations and to put a polarizer in front of each detector pixel. The array of polarizers are arranged in groups of four where the axis of the polarizers are at 0, 45, 90, and 135 degrees [34]. It can be shown that the phase shift between the two interfering beams goes as twice the angle of the polarizer [35]. In this way, four phase-shifted beams are obtained simultaneously. As long as there is enough light to make a short exposure, the effects of

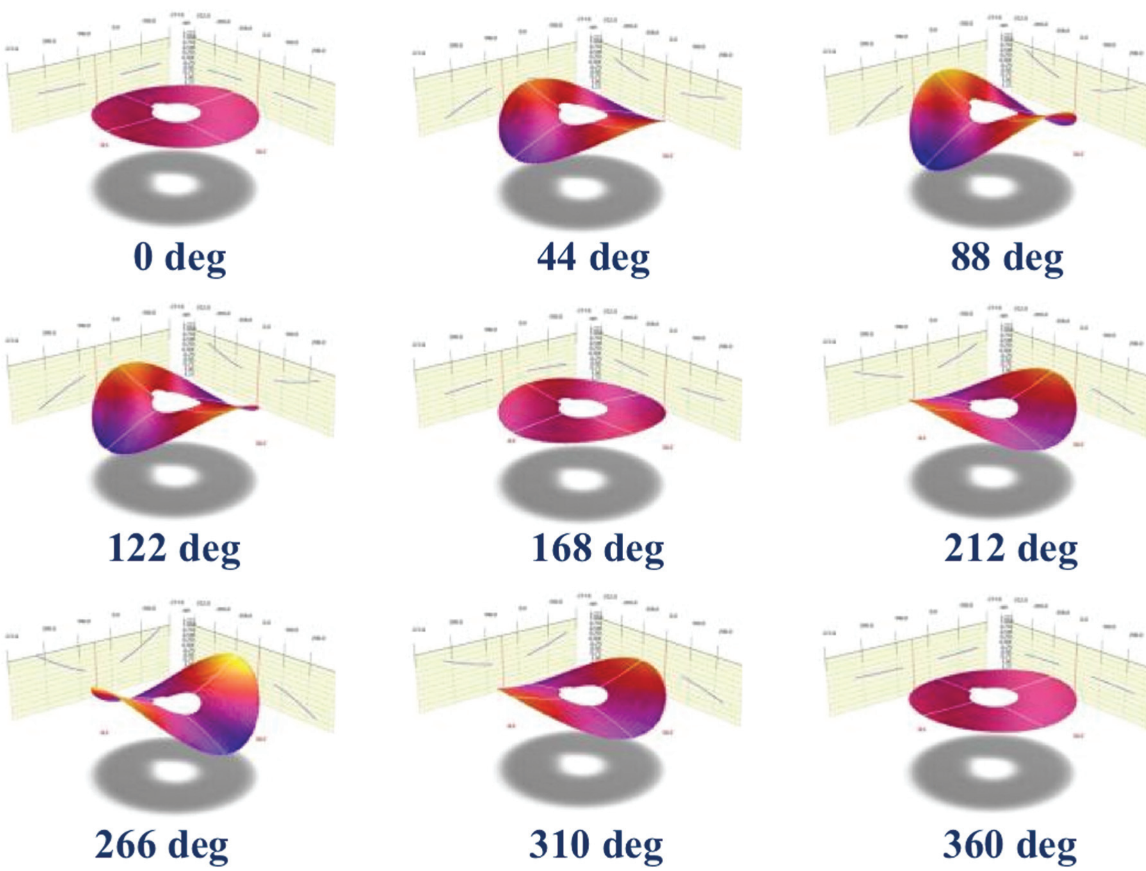


Fig. 4. Three-dimension contour maps showing shape of vibrating surface as a function of time.

vibration are eliminated and precise measurements can be performed in the presence of vibration; many measurements can be averaged to reduce the effects of air turbulence. 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, as shown in Fig. 4. Techniques such as this are extremely useful for increasing the applications of laser-based interferometric metrology.

Frequency Combs

An important recent development is the use of frequency comb lasers for determining the absolute distance to an object. In 2005 John Hall and Theodor Hänsch shared half the Nobel Prize in physics for development of laser-based precision spectroscopy, including the use of frequency comb lasers.

Frequency comb lasers [36] have the potential to revolutionize long-distance absolute measurements by allowing better than sub-micrometer accuracy of distances up to, and possibly beyond, 10,000 km. Comb lasers are pulsed (ultrafast) mode-locked lasers with a precisely controlled repetition rate and pulse phase. Stabilizing the output of a femtosecond laser provides a spectrum of well-defined frequencies. The periodic pulse train of a femtosecond laser generates a comb of equally spaced frequencies for multi-wavelength interferometry. It is possible to link the time-of-flight domain of long-distance measurement with an interferometric measurement to obtain nanometer accuracy. The basic concept is to use this incredibly regular pulse structure to measure a distance in units of the pulse separation length. For accuracies down to the 10-μm level, it is sufficient to use Time of Flight measurement [37,38]. Sub-wavelength accuracy in the nanometer range can be obtained using spectral interferometry where the distance is obtained by determining the slope of the phase as a function of the optical frequency [39,40]. It is believed that distances of 500 km can be measured to accuracies better than 50 nm.

It continues to be a very exciting time for the use of lasers in optical metrology. With the combination of new lasers, modern detectors, computers, and software, the capabilities and applications of metrology are astonishing.

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