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Surface Profilers, Multiple Wavelength, and White Light Interferometry

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15.1. INTRODUCTION TO SURFACE PROFILERS

Over the last 25 years driven by both the development of new technologies such as fast computers and solid state devices and the necessity to precisely inspect these increasingly tiny engineering surfaces, the field of surface metrology has exploded in both its technological sophistication and its range of application. Advances in illumination sources, such as lasers, and in solid state detectors and optoelectronic devices in general have fueled the development of a wide range of instruments that can not only map surface topography but also determine other features such as displacement or dispersion. Innovative techniques and technologies have greatly increased the range of measurable objects, so now even difficult surfaces with high slopes or steps and narrow, deep trenches can be measured. Many of these surface profiling techniques were developed from distance measuring or focus detection techniques, and they often require scanning to obtain the surface profile. This chapter describes instruments such as the stylus profiler, scanning probe microscope, confocal microscope and the interferometric optical profiler that are most often used to determine surface topographies of not only very small, typically engineering surfaces, but also smooth and large surfaces such as aspheres and glass plates.

The first part of this chapter describes scanning probe microscopes and stylus profilers. Then optical methods are detailed with a specific focus on techniques developed over the last 15 years that have found commercial and industrial application. This section describes both interference microscopes that employ both monochromatic and white light illumination and also confocal microscopes that have recently been fairly used to measure engineering surfaces. The next part of this chapter reviews work done in multiple wavelength interferometry, namely two and multiple wavelength, wavelength scanning, and spectrally resolved white light interferometry. White light and multiple wavelength techniques are often applied to other methods, such as speckles and holography as well as fringe and structured light projection procedures. Finally, we provide a short overview of optical ranging techniques and polarization interferometers.

15.1.1. Contact Profilometers

Stylus Profilers and Scanning Probe Microscopes. Often described as contact profilers, or tactile sensors, because they use a probe to scan along the surface of an object, the forces applied to the tips of these probes are now so minute that it is difficult to call them contact instruments anymore. These instruments trade relatively slow measurement speed for excellent lateral resolution, often below the optical resolution of optical microscopes. The stylus profiler, one of the first to be developed, is both inexpensive to build and easy to use; for these reasons it is a standard in many mechanical and optical shops. The scanning probe microscope was developed later but is now common in both labs and the semiconductor and micro-electromechanical systems (MEMS) industries, because of its subnanometer vertical and lateral resolution and its ability to measure many different material properties. The profile of larger objects can be measured using a coordinate measuring machine (CMM) that uses a larger probe and is able to work in scanning mode.

15.1.2. Optical Profilometers

Optical Focus Sensors. Instead of using a mechanical probe as contact profilers do, a broad group of instruments called optical profilometers use an optical focus sensor to obtain profile measurements. A few optical focus sensing techniques that have been developed into commercial profilometers are detailed in this chapter.

Confocal Microscope. The most commercially successful of the optical focus sensing systems is the confocal microscope, which was initially developed to examine biological samples and more recently has found applications for testing engineering surfaces. The confocal microscope is a modified conventional microscope with a single point source and a pinhole placed in front of the detector to filter out spurious light so as to obtain a more distinct irradiance signal at the focus position.

Two and Multiple Wavelength Interferometry. The first interferometric optical profilometers used monochromatic illumination and phase shifting methods. Phase

shifting methods generated the highest measurement precision; however, monochromatic illumination limited the measurement range. In order to increase the range of these measurements, two and multiple wavelength techniques were developed. Today, the principles of two and multiple wavelength interferometry can be found in holographic and speckle techniques and are applied to the testing of large objects using a fringe projection and structured light techniques (see Chapter 16).

15.1.3. Interferometric Optical Profilometers

White Light Interferometry. White light interferometric systems have long established themselves as the leading optical profilometers for measuring engineering surfaces. White light interferometry can be thought of as an optical focus sensor where the position of the interference signal determines best focus. Typically, these setups consist of a conventional microscope outfitted with an interferometric objective. The advantage of interferometric systems over most other optical and stylus profilers is their ability to scan the entire field rather than proceed by point to point scanning. Because the whole area is imaged at the same time, lateral scanning becomes unnecessary, which greatly speeds up the measurement process.

Spectral Interferometry. Another group of interferometers is based on the observation of interference fringes for a very large number of wavelengths called spectral interference fringes. Spectral interference can be obtained by using a source with a tunable wavelength or by placing a dispersive element at the exit of the interferometer. These systems are called wavelength scanning interferometers and spectrally resolved white light interferometers, respectively. Rather than detecting best focus at each point a spectrometer (or charge coupled device, CCD) detects the fringe frequency which carries information about the object's position. This method bypasses the need for mechanical axial scanning.

Optical Ranging Sensors. The techniques used in interferometric optical profilometers are often built on or independently developed from techniques found in interferometric optical ranging sensors, which typically measure absolute distances or lengths at a single point. For single point detection, much faster detectors and optoelectronics as well as task-specific signal processing techniques can be employed.

Polarization Interferometers. Some interferometers utilize the polarization properties of light so as to have two beams traveling almost the same path in the interferometer like in the differential interference microscope. Polarization interferometers that use polarization to shift the phase often can be made to be insensitive to vibrations. The polarization properties of light are effective in evaluating some properties of submicron structures.

15.1.4. Terms and Issues in Determining System Performance

All profilometers need to be carefully calibrated especially when measuring small objects such as MEMS. Various aspects of system performance are checked against

artifacts that have a traceability certificate to some primary standard. The most common artifact is a step; for example, a step artifact is used for vertical scale calibration while a sample with an etched binary grating is often used for lateral magnification calibration. Other artifacts like sinusoidal gratings or surfaces of different roughness are also used to verify a system's performance. Ideally all measurements should be traceable to the same units. Standards institutes, such as the National Institute of Standards and Technology (NIST), Physikalisch-Technische Bundesanstalt (PTB) or National Research Council (NRC) in Canada, are continuously developing artifacts and measured parameters so as to provide accurate calibration and verification of systems. Artifacts become standards after they are measured using traceable stylus profilometers.

Manufacturers often give, and customers require, as a parameter of system performance the value the vertical resolution; however, rarely is the information provided as to how the manufacturer measured and calculated the parameter and on which artifact. Without knowing how the value of a particular parameter is determined, comparing these values across different manufacturers or systems is worthless.

Along with determining system performance, the other two really important issues in measurement are repeatability and reproducibility. In general repeatability is defined as one sigma standard deviation of a parameter of an object measured multiple times over a short period of time and without any changes in the system. Reproducibility refers to the distribution of multiple measurements over a longer period of time and under different measurement conditions. Specifications for a system are typically presented in terms of the repeatability and reproducibility of certain parameters of a measured object. It is important that the measurement procedure and reported specification values are well defined and agreed upon by user and manufacturer.

Two terms that are often misunderstood in surface metrology are accuracy and precision. Accuracy determines how close the measured value is to the true value (for example, the value of the certified artifact), and precision refers to the distribution of the measurement and can be expressed in terms of repeatability or reproducibility.

15.2. CONTACT PROFILOMETERS

The two main contact profilometers are the stylus profiler and scanning probe microscope, and they use a tactile probe to measure the surface profile. Their measurements differ in lateral and vertical ranges and their resolution, and thus they find different applications. The scanning probe microscope, in addition, measures sample-tip interaction, which allows for the measurement of materials different properties.

15.2.1. Stylus Profilers

Stylus profilers move a small-tipped probe across the surface and sense height variations of the tip to determine the surface height profile. Stylus profilers can

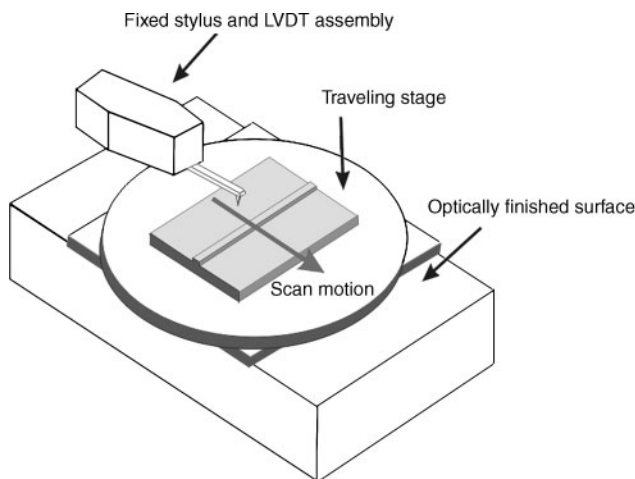


FIGURE 15.1. Schematic of stylus profiler with LVDT as the motion detector. Courtesy Veeco Instruments.

measure surfaces up to about one millimeter in height. These profilers work very much like a phonograph; usually the surface is moved under the stylus tip, but the stylus may also be moved over the surface. The vertical motion of the stylus is typically detected by a linear variable differential transformer (LVDT) and this signal is converted to height data. The styli are made of a hard material such as diamond with a tip radius of curvature between 0.05 and 50 μm , which determines the instruments' lateral resolution. To ensure that the test surface is not damaged during measurement, the load of the stylus tip on the surface is variable from 0.1 mg up to 50 mg. A minimum load that keeps the stylus on the surface is chosen so that the surface is not deformed as the stylus moves across it. A schematic of a stylus profiler with LVDT as the motion detector is shown in Figure 15.1. Other schemes of tip guidance and its motion detection are possible (Whitehouse, 1997).

The stylus tip shown in Figure 15.2 has a 45° cone angle, but many other shapes and angles are possible. Both the shape and the angle determine the penetration depth of the tip on the test surface. The output of these profilers is the convolution of the size and shape of the stylus tip with the surface profile. Choosing the configuration of the tip is extremely important to ensure penetration to the bottom of steep trenches and prevent rounding off of high surface peaks. Figure 15.3 shows the effect of a stylus tip on the measurement of trenches with various aspect ratios.

However, while a tip radius that is smaller and sharper allows the stylus to follow the shape of the surface more easily, if the tip is too sharp, the local force on the surface over the tip area may be so great that the surface becomes locally deformed. If the surface elastically deforms, the sample will not be damaged but the surface profile may be inaccurate. If the surface plastically deforms, the sample may be permanently damaged and the surface profile will be inaccurate. New, low force

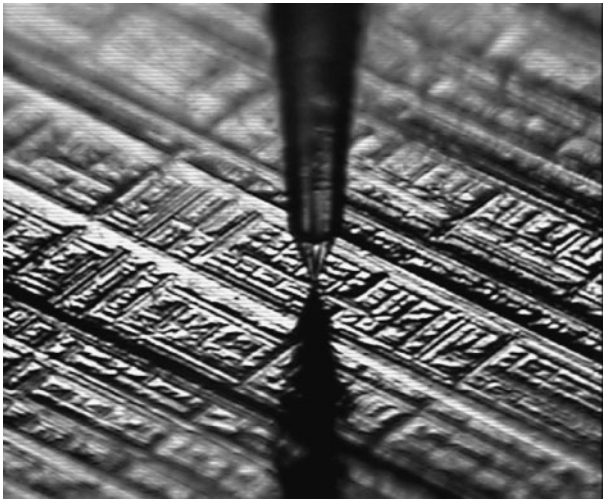


FIGURE 15.2. A stylus tip with a $0.2\text{ }\mu\text{m}$ radius and a 45° cone angle maps the surface of a roughness comparator strip. The camera attached to the stylus profiler observes the position of the tip with respect to the object. Courtesy Veeco Instruments.

technology (less than a milligram tip loading) allows for the measurement of soft materials such as a photoresist. In addition, when a small-radius stylus is used, the scan speed must be greatly reduced, and similarly the stylus load must be reduced to ensure a precise measurement. The most accurate stylus profilers have tip radii of tenths of a micrometer or less and tip loadings of milligrams or less. These profilers also may require enclosures and vibration isolation systems, and completing a scan of a few thousand data points can take many minutes.

The lateral resolution of stylus profilers is determined by the radius of the stylus tip as well as the surface shape and the sampling interval between data points. For a stylus with a spherical tip measuring a sinusoidal surface profile, the shortest

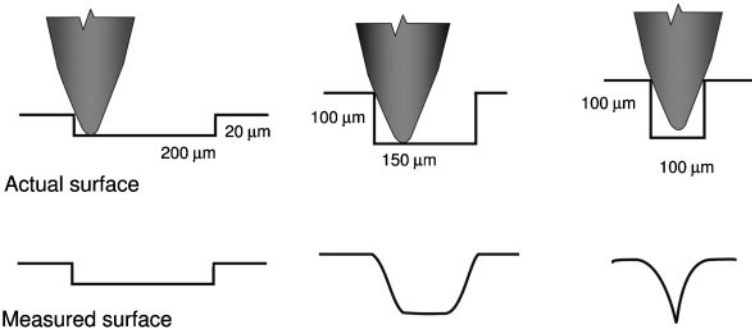


FIGURE 15.3. The convolution of a $25\text{ }\mu\text{m}$ radius stylus tip with a surface profile.

measurable wavelength (period) d of the sinusoid depends not only on the stylus radius r but also on the amplitude of the sinusoid a (Bennett and Dancy, 1981). The equation describing the shortest measurable period d is

$$d = 2\pi\sqrt{ar} \quad (15.1)$$

Because two samples per sinusoidal period are required to reconstruct a sinusoid, the lateral resolution will be $d/2$. This means that for a stylus of 10 μm radius measuring 1 nm surface height variations, the lateral resolution is approximately 0.6 μm . To ensure sufficient resolution, it is best to oversample and measure at least four samples per lateral resolution element (Bennett and Mattson, 1989). Lateral resolution and transfer functions for more complex surface features can also be determined (Al-Jumaily et al., 1987; Bennett and Dancy, 1981). The profile (and radius) of the stylus tip can be determined by viewing the tip with a scanning-electron microscope (SEM) or by scanning it over the edge of a razor blade (Vorburger and Raja, 1990). The smallest stylus tips available on the market have a radius of about 50 nm, they are often etched with a focused ion beam (see Fig. 15.4). These small tips significantly improve the lateral resolution of the profiler.

The cone angle of the stylus tip also determines the measured aspect ratio of the trenches, which typically is 1:1 for a common 60° cone angle. With the necessity of measuring structures with high aspect ratios such as MEMS, sharp styli have been developed to measure trenches with aspect ratios as high as 10:1. Custom tip

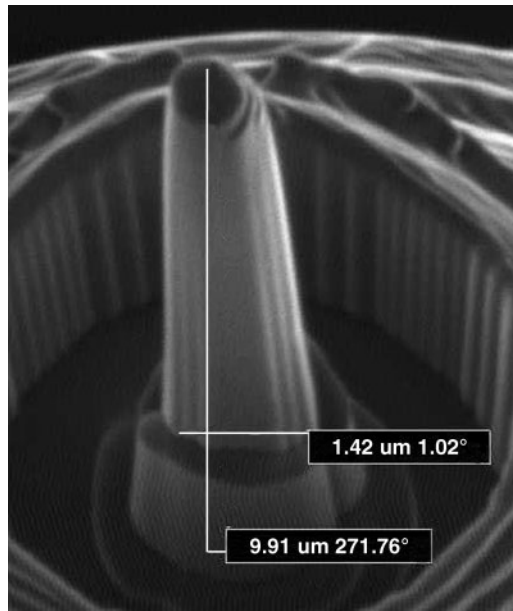


FIGURE 15.4. Scanning electron micrograph of 50 nm radius stylus tip. Courtesy Veeco Instruments.

geometries, that is “chisel-types,” can also be fabricated with today’s technology to measure challenging samples, like solder bumps in integrated circuit packages.

Most stylus profilers have reference datums of some type to ensure measurement accuracy (Vorbürger and Raja, 1990). The reference surface can be a skid, that is, moved across the surface with the stylus, or can be a separate reference surface so that another large-radius probe is moved across in a fixed relationship to the measuring stylus. References can also be created using flexures (Vorbürger and Raja, 1990). Using a large radius skid near the stylus is the easiest way to generate a reference, but this technique can cause errors and will remove shape and figure information. A separate reference is most accurate but can limit the length of the scan and the measurable height variation. Optical flats with flatness $\lambda/20$ provide a very stable reference.

Stylus profilers are normally calibrated using traceable height and roughness standards; these standards can be purchased from VSLI Standard Incorporated or PTB (Physikalisch-Technische Bundesanstalt, Germany). The most common standards are step heights of chrome on glass. The step is measured periodically with the profiler to ensure calibration and a scaling factor is calculated to apply to the profile data. Some stylus profilers are not linear over their entire height range; it is important to calibrate the instrument with a step height which is close in height to the test samples being measured. When surface roughness is being determined, it is better to use a roughness standard than a step height standard because both lateral resolution and surface height variation need to be considered. These standards are available in a number of different types. The most common have a sinusoidal height variation with a given amplitude and a number of different spatial wavelengths. Roughness standards are also available as square-wave gratings. Because the stylus may not get down into the valleys and can round off peaks, the sinusoidal standards give a more accurate indication of instrument performance at a single spatial frequency.

Stylus profilers are capable of measuring surface roughness with a root-mean-square (RMS) as small as $0.5 \text{ \AA}$ with lateral resolutions of 0.1 to $0.2 \text{ }\mu\text{m}$. The instrument noise measured at a single point without scanning the surface can be as small as $0.5 \text{ \AA}$ RMS. Stylus profilers are capable of measuring 100 nm step height with repeatability of $6 \text{ \AA}$ and $60 \text{ }\mu\text{m}$ step height with 7 nm repeatability. Since the stylus profiler is a contact instrument, in order to measure film thickness, the step of the film to substrate is needed.

The stylus profiler has a wide range of applications in general metrology and the semiconductor industry due to its high lateral and vertical range. Stylus profilers are often used when profiles of long surfaces up to 200 mm in length are needed. Profiles of this type are typically obtained in single scans and then stitched together. Multiple scans at low force reduce the possibility of damaging the sample. Other typical applications include a scratch test for measuring the thickness and hardness of a protective coating, wafer planarity, and etch depth rate uniformity across a wafer, testing the stress that thin films induce on a wafer, RGB color filters on flat panel displays, and flip-chip bumps, and monitoring wet etching of MEMS. Figure 15.5 shows the results of a few applications of stylus profiler measurements. Some

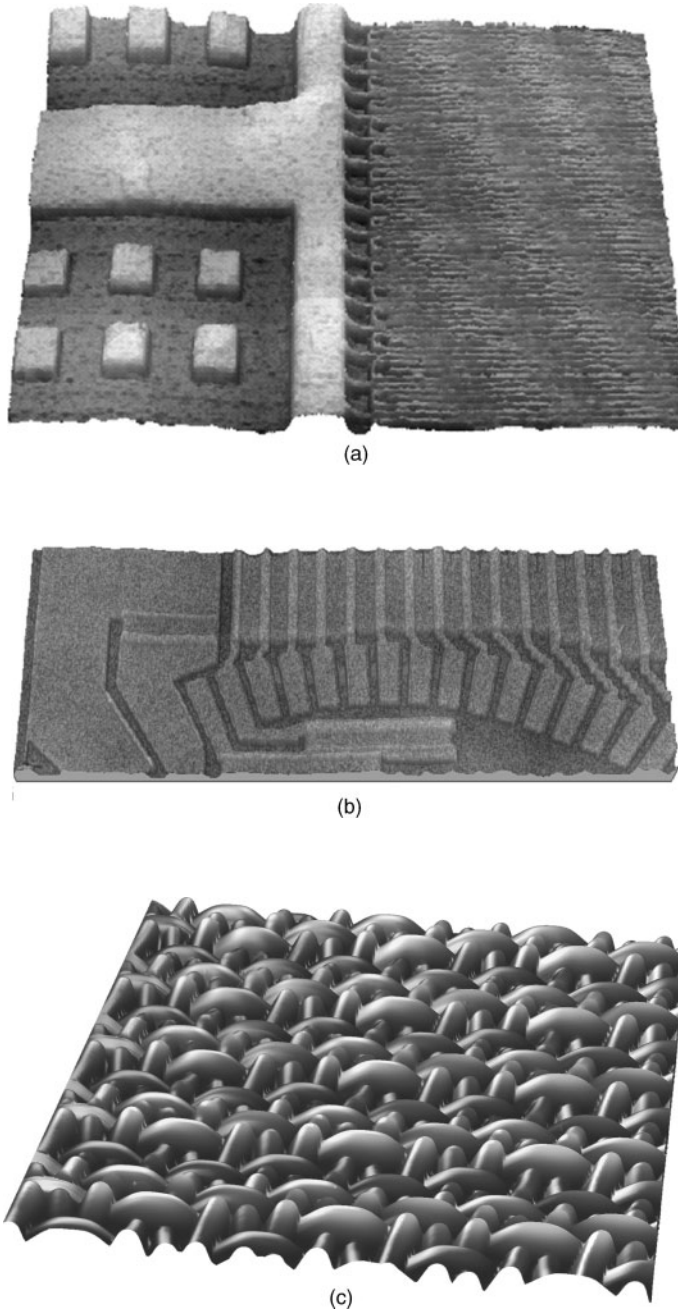
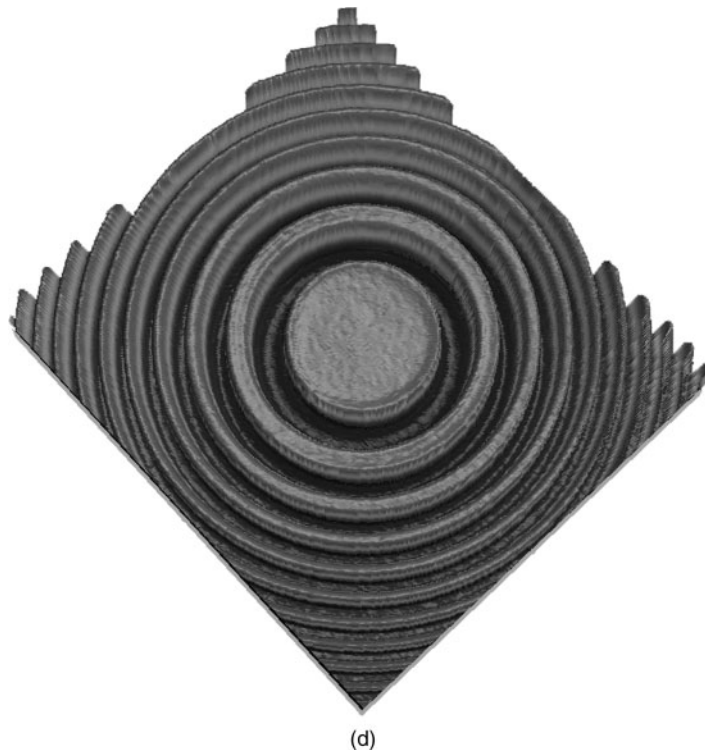


FIGURE 15.5. A few examples of stylus profile measurements: (a) Cu line connect $24\ \mu\text{m} \times 45\ \mu\text{m}$ (b) automotive sensor, scan $40\ \text{mm} \times 15\ \text{mm}$, (c) polyester mesh, scan $14\ \text{mm} \times 14\ \text{mm}$ (d) binary optics, scan $240\ \mu\text{m} \times 210\ \mu\text{m}$. (a–b) courtesy KLA-Tencor, (c–d) courtesy Veeco Instruments.



(d)

FIGURE 15.5. *(Continued)*

profilometers are designed specifically to measure aspheric surfaces and their roughness. These systems can measure aspheres up to 12 mm in width, 38 mm in height and over 200 mm in length. A review of recent advances in aspherics measurements using stylus profiles was done by Scott (Scott, 2002).

An overview of surface metrology including the stylus profiler, surface characterization and a review of optical methods can be found in a number of sources (Stout and Blunt, 1994; Thomas, 1999; Lehmann, 2003; Whitehouse, 1997, 2003).

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15.2.2. Scanning Probe Microscopes

Scanning probe microscopes (SPMs), which are capable of obtaining atomic scale resolution, work by moving a fine tip in close proximity to a test surface. They usually scan within a few angstroms of the surface, but the tip can also be in direct contact under forces smaller than a nano-Newton. The first microscope of this type was a scanning tunneling microscope (STM) built by Binnig and Rohrer (Binnig and Rohrer, 1982, 1985) who won the 1986 Nobel Prize in physics for their work in this field. The most popular SPM is the atomic force microscopes (AFM), also known as the scanning force microscopes (SFM).

Numerous modes of operation are possible on the AFM, including magnetic force microscopy (MFM) and electric force microscopy (EFM). The field of scanning probe microscopy is changing rapidly and new probe types are constantly being introduced for a wide variety of applications. With so many different probe types, it is possible to find one that is appropriate for almost any surface to be tested, from integrated circuits to biological objects. Reviews of SPMs have been written by Hansma and Tersoff (1987); Ruger and Hansma (1990), Sarid (1991), Wickramasinghe (1989) and more recently by Bhushan et al. (2003), Bonnell (2000), Cohen and Lightbody (1999), Magnov (1996). This section will concentrate on two types of SPMs: STM and AFM.

Scanning Tunneling Microscopes. In the STM, a metal tip is moved toward the electrically conducting or semi-conducting test surface until a tunneling current between the tip and test surface is detected. In order to sense tunneling current, voltage must be applied between the probe tip and the test surface. For atomic resolution, the end of the tip has only one atom interacting with the test surface. This tunneling current can only be sensed when the probe is less than 1 nm away from the surface. As the probe is moved closer to the surface, the tunneling current increases exponentially. A change of 0.1 nm causes the current to change by factor of 10 giving STM atomic scale measurement sensitivity. The probe is usually scanned a few angstroms above the surface in a raster fashion using piezo-electric transducers (PZTs). The necessity for a conducting test surface limits the application of the STM, and image resolution is highly dependent on the tip geometry (van Loenen et al., 1990).

Figure 15.6 is a schematic of an STM, consisting of a fine probe tip mounted on x, y, z PZT translators. The STM can operate in either constant-current or constant-height mode. The constant-current mode uses a feedback loop to vary the height of either the probe or the sample during the scan and keep the tunneling current at a constant value. Constant-height mode measures the tunneling current as a function of position while the tip (or the sample) is kept at a constant height. Because larger

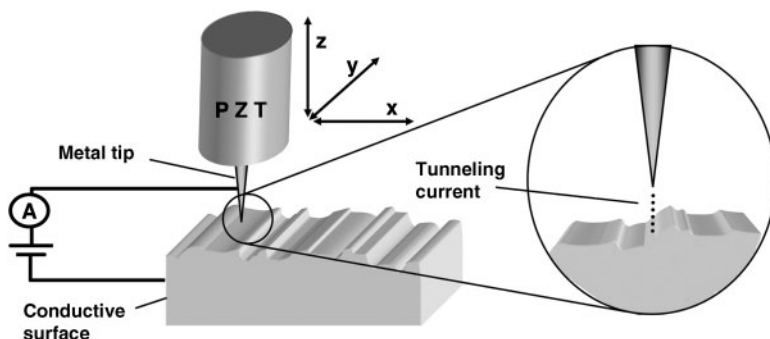


FIGURE 15.6. Schematic of a scanning tunneling microscope (STM), which is able to measure topographies of conductive surfaces with sub-atomic lateral and vertical resolution.

height variations can be measured, constant-current mode is most often used. Constant-height mode is faster, but the tip can easily crash into the surface if the surface is rough. Crashing not only ruins the tip, but can also harm the test surface.

STMs were originally developed for atomic-resolution applications in a vacuum (Binnig and Rohrer 1982); now they are being used in air and can scan areas larger than 100 μm . Scan range is determined by the PZT; the tradeoff is between range and resolution with longer-range PZTs generally having less resolution. Just as optical microscopes employ various magnifications for measuring with different lateral resolutions and over different sized fields of view, STMs use scan heads with a variety of probe sizes (see Fig. 15.7) and scan ranges in order to change lateral and

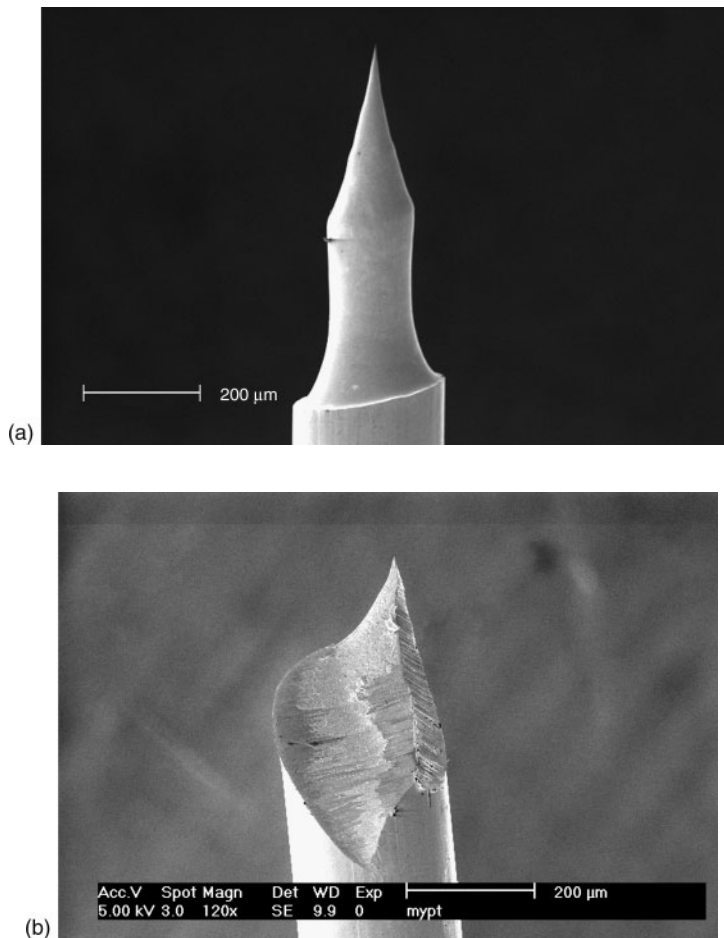


FIGURE 15.7. STM tips can be produced from (a) tungsten wire by computer controlled etching, or (b) tungsten or platinum/iridium wire by mechanical cutting. The latter is recommended for atomic imaging. Courtesy Veeco Instruments.

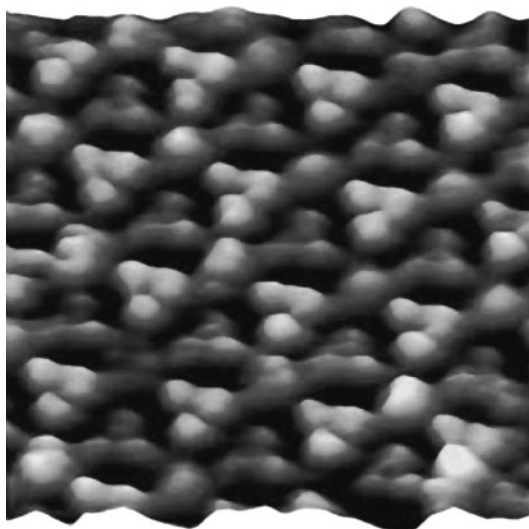


FIGURE 15.8. STM image of a monolayer of liquid crystal with graphite-solution interface. 36 nm $\times$ 36 nm scan. Courtesy Veeco Instruments.

vertical resolution and scan range. The larger STM scan ranges overlap the measurement span of high-magnification optical profilers and high-resolution stylus profilers. Because STMs require conducting surfaces to produce a tunneling current, surfaces such as glass cannot be measured. Even with these limitations, STMs have been used to evaluate optical surfaces (Dragoset et al., 1986; Dragoset and Vorburger, 1987; Schneir et al. 1989). Figure 15.8 shows a shaded solid plot of a molecular pattern of a monolayer of liquid crystal film on a conductive graphite-solution interface measured using an STM. The overview of STM's theory, related scanning probe techniques and application were described by Güntherodt and Wiesendanger (1994), Wiesendanger and Güntherodt, (1995, 1996).

Atomic Force Microscopes. The atomic force microscope (AFM) is an extension of the STM (Binnig et al., 1986). In addition to conductive surfaces, the AFM is able to map nonconductive samples by using the force of the tip-surface interaction as the control parameter rather than the tunneling current. Two types of atomic forces can be used for AFMs, a repulsive force and an attractive force; these forces correspond to two basic AFM modes of operation called contact and noncontact modes as shown in Figure 15.9.

In repulsive force mode, the probe acts like a phonograph needle as it is moved essentially in contact with the surface. The tip is typically less than 10 μm long with a 2–10 nm end radius. The tip is located at the free end of a cantilever (made usually of very flexible material like silicon or silicon nitride) that is typically 100–500 μm long and 2–10 μm thick. A silicon type cantilever and its tip are shown in Figure 15.10. Forces between the tip and the sample surface cause the cantilever to bend (cantilever deflection) as the AFM scans the sample surface. The deflection of the cantilever is

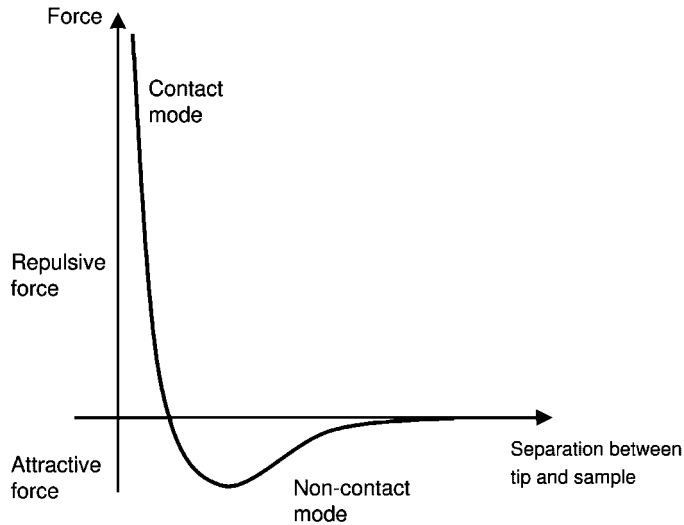


FIGURE 15.9. Force-and-mode type of operation versus tip-to-sample separation.

measured to determine surface topography. Often, the cantilever is so flexible that the tip-sample contact force is smaller than the force that holds the atoms of many solids together.

Deflection can be measured in a number of ways. Alexander (Alexander et al., 1989) developed a readout system that looks at the deflection of a laser beam reflected off a mirror mounted on the cantilever. Deflection measurement is based on the optical triangulation principle. Another readout technique, developed by Sarid (Sarid et al., 1988), uses feedback into a diode laser from the reflection off the back of the cantilever; this cantilever, however, can also be made from piezoresistive material so that its deflection can be measured electrically. Figure 15.11 shows both optical types of readout and Figure 15.12 shows an AFM measurement of the topography of a patterned Si/SiN and metallic glass using laser deflection readout.

Attractive force AFM, also known as non-contact mode, will not damage a sample because it never touches the surface. Because the attractive force is very small, the tip is oscillated at a high frequency, and what is detected is the change in the amplitude and phase of the vibration due to losses or gains in kinetic energy during tip-sample interaction.

A very effective AFM intermittent contact mode called TappingMode (Zhong et al., 1993; Cleveland et al., 1998) has become the most common AFM approach. This patented technique (Virgil and Gurley, 2000) maps topography by lightly tapping the surface with a probe, which is oscillating at a frequency close to the cantilever's resonance frequency. Figure 15.13 shows a schematic of TappingMode. The amplitude of the tip oscillation reaches up to a few tens of nm. This large amplitude of oscillations ensures that the tip does not get stuck in the liquid layer at the surface of the test object, which can happen in noncontact AFM. TappingMode overcomes some of the limitations of both contact and noncontact AFM by eliminating lateral shear forces that can

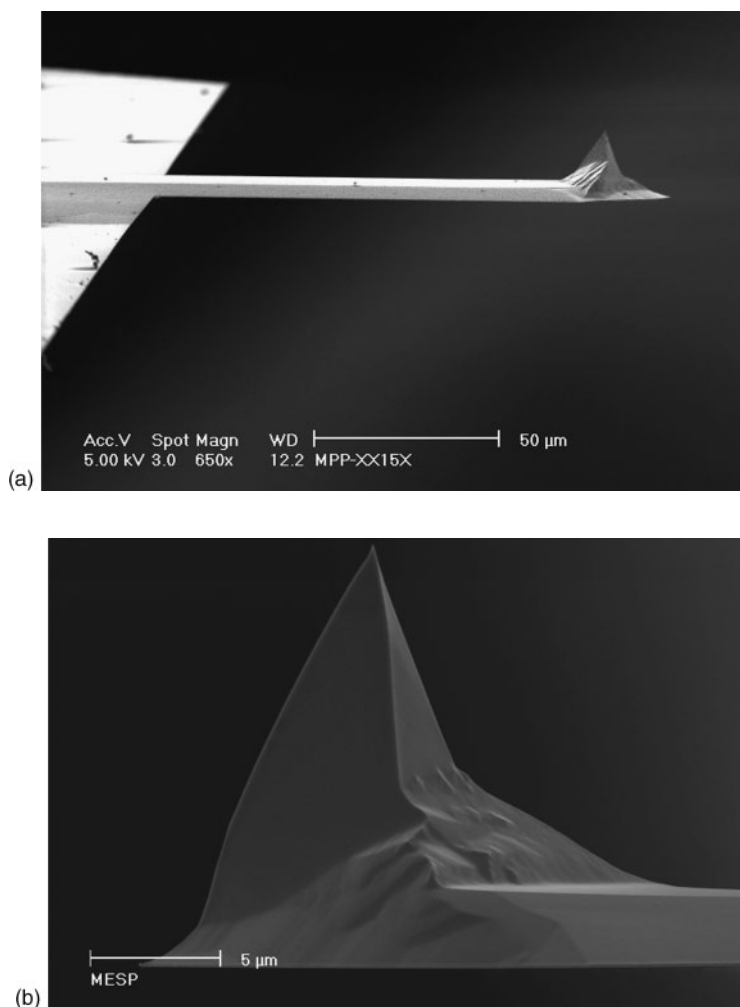


FIGURE 15.10. Scanning electron microscope images of (a) a silicon cantilever and tip and (b) tip only used in AFMs. Courtesy Veeco Instruments.

damage soft samples and reduce image resolution. Figure 15.14 shows the measurement of a strand of DNA using TappingMode. TappingMode also allows for the measurement of surfaces with height variations up to several micrometers.

AFM can characterize not only the topography of a sample but also many other sample properties by applying varying motions and signals that drive the probe. For example, variations in material composition, adhesion, friction, viscoelasticity, and electric and magnetic material properties can be determined. Figures 15.15 and 15.16 show the measurement of the surface topographies and the electrical and magnetic properties of samples.

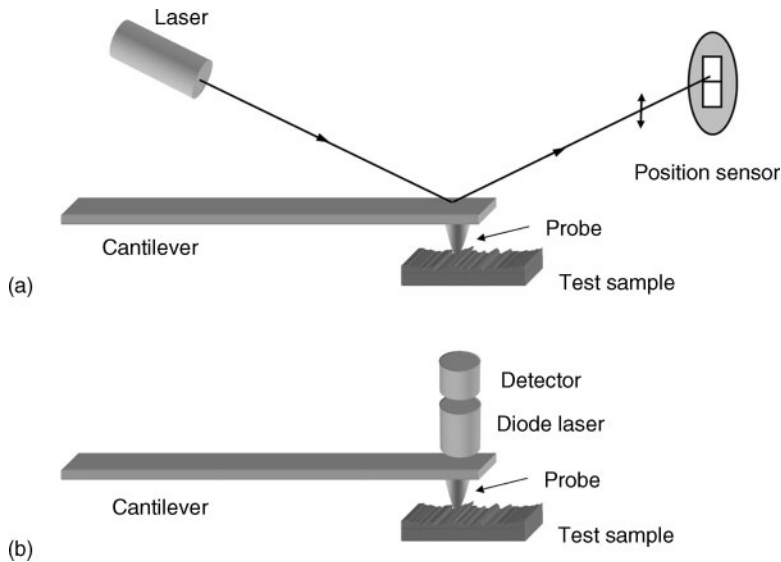


FIGURE 15.11. Schematic of AFM cantilever's tip position readout. (a) Optical lever readout, (b) diode laser readout.

The AFM is also capable of determining changes in the properties of a sample surface by mapping the phase lag between the periodic signal that drives the tip and the oscillations of the tip. A recently developed technique called Torsion Resonance Mode (TRmodeTM) (Su et al. 2003) measures and controls dynamic lateral forces between the probe tip and sample surface. Characterization of torsion oscillations of the cantilever TRmode allows for nanoscale examination of in-plane anisotropy of a sample. A review of different AFM modes and applications of AFM to measurement of microsystems like MEMS was done by Serry and Schmit (Serry and Schmit, 2006).

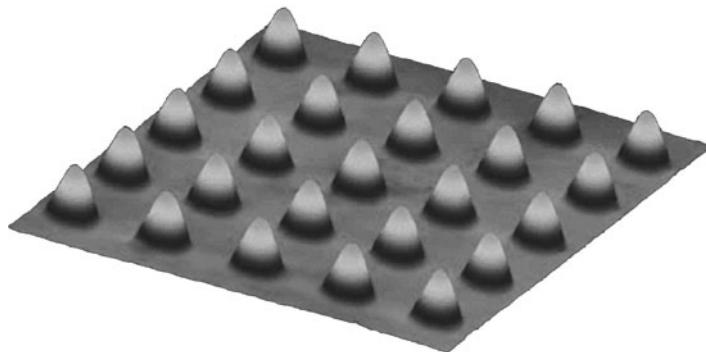


FIGURE 15.12. AFM image obtained in contact mode of a pattern of 80 nm tall features in a Si/SiN substrate produced by ion irradiation through a stencil mask. The features are 1 micrometer in diameter and 1 micrometer apart, 10 μm $\times$ 10 μm scan. Courtesy Veeco Instruments.

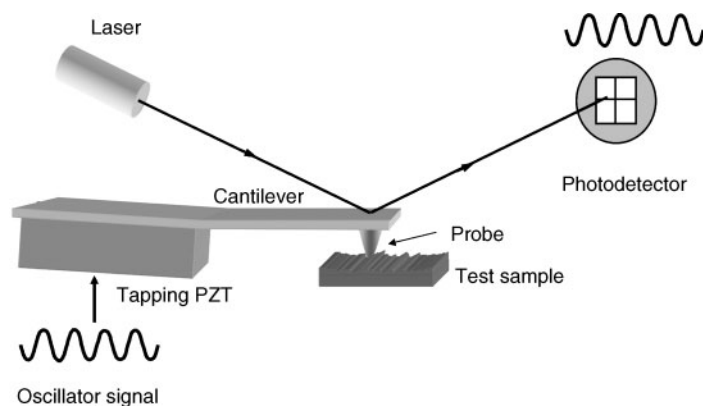


FIGURE 15.13. Schematic of signal detection in AFM Tapping Mode. The probe is kept at a constant level above the sample, which results in a constant amplitude signal. Changes in the amplitude of the signal indicate that the distance between the cantilever and object needs to be changed.

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A number of authors have discussed the uses of the AFM in biological and medical science (Morris, 1999; Bhanu et al., 2002; Braga and Rica, 2003). The AFM provides important ways for looking at biological samples such as allowing for structural analysis of cells and their functionality. Example of cell measurement is shown in Figure 15.17.

15.2.3. Comparison of AFM and Stylus Profiler

Both the stylus profiler and the later-developed AFM scan across the surface in direct contact with the object at low force. Recent developments in nanotechnology and electronics have pushed the development of the AFM; it is no longer simply a surface

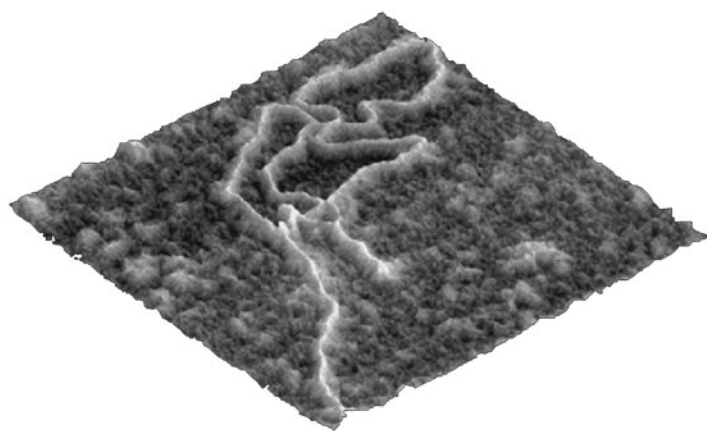


FIGURE 15.14. AFM Tapping Mode provides a clear and reproducible resolution of lambda phage DNA on mica. This is a 1 μm scan. Courtesy Veeco Instruments.

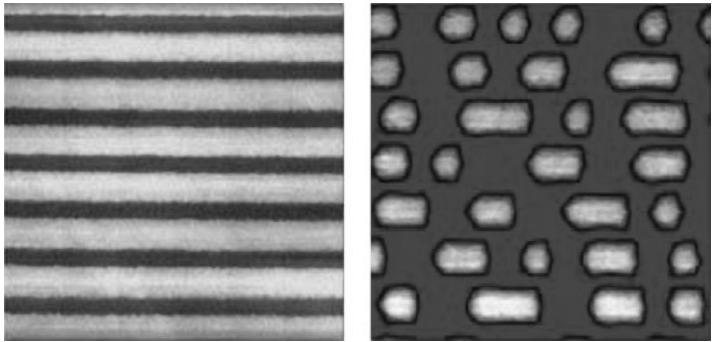


FIGURE 15.15. Surface topography (left) and electrical (right) properties of a DVD-RW. The electrical properties produced using the electron force microscope capabilities of the AFM show amorphous bits formed with the phase change on the crystalline area. Scan area $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$. Courtesy Veeco Instruments.

topography instrument, for now it can measure a wide range of surface characteristics. The stylus profiler and AFM have complementary capabilities for three-dimensional surface metrology and in fact are sometimes merged together on one platform to fulfill specific industrial needs such as the measurement of semiconductor wafers. Topographies obtained with these instruments are not sensitive to the optical properties of the measured surfaces, and both instruments are well suited for measuring samples made of different materials and films. Their basic characteristics, as compared to the optical profilers described later in this chapter, are collected in Table 15.1. The table represents typical values at the time of publication. Figure 15.18 shows typical measurement ranges for three types of profilometers.

The broad field of microscopy, including optical, electron and scanning probe microscopy, is reviewed by Hellmuth (2004). A comparison of stylus profiler and AFM measurements on optical surfaces can be found in Bennett et al. (1991).

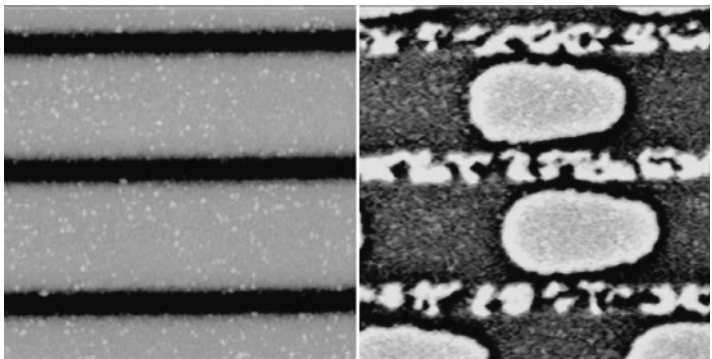


FIGURE 15.16. Bits on a magneto-optical disk. The left image shows surface topography with tracks delineated by grooves. The magnetic force gradient map (right) shows bit edge roughness as well as virgin domain structure in the grooves with features as small as 50 nm. Scan area $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$. Courtesy Veeco Instruments.

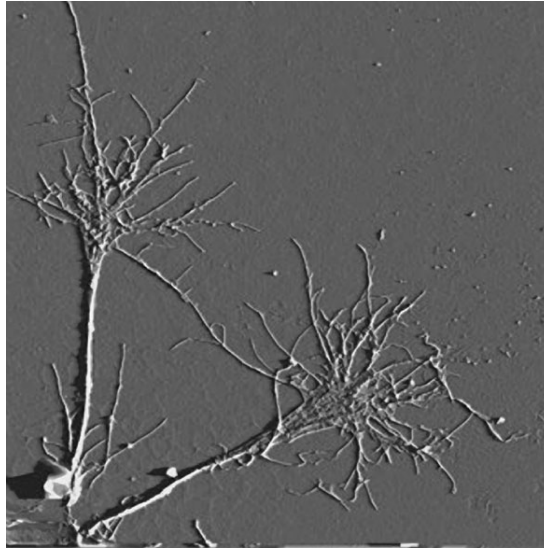


FIGURE 15.17. AFM image of a retinoic acid-induced differentiation of human SH-SY5Y neuroblastoma cells (Dendrites). 100 μm scan. Courtesy Veeco Instruments.

15.3. OPTICAL PROFILERS

Rather than using a mechanical probe to map surface topography, an optical probe that does not contact the test surface may be used. Optical probes determine shape by sensing the best focus position on a test object. Optical profilers generate measurements by sensing focus at a single point on the surface and adjusting the height of the

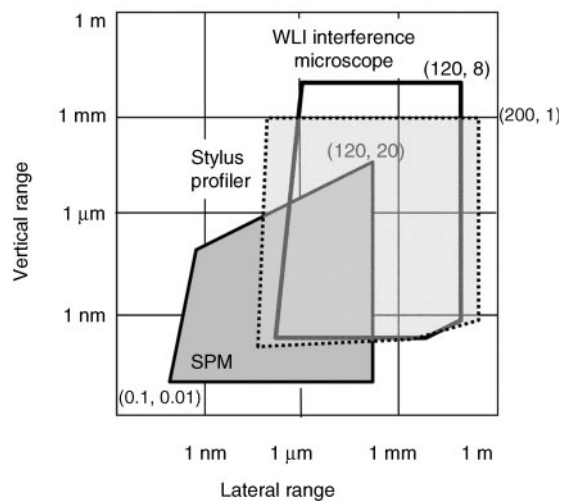


FIGURE 15.18. Plot of measurement ranges for SPM, stylus, and white light interference profilers.

TABLE 15.1. The main characteristic parameters of a scanning probe microscope, stylus profiler, white light interferometric optical profilometers, and confocal microscope.

	Atomic force/ scanning tunneling microscope	Stylus profiler	White light interferometric optical profiler	Confocal microscope
X,Y resolution	2–10 nm AFM 0.1 nm STM	50 nm (stylus radius dependent)	0.5 μm (NA objective dependent)	0.5 μm (NA objective and lateral sampling dependent)
Z resolution	0.1 nm AFM 0.01 nm STM	0.25 nm	0.3 nm	1–20 nm (Dependent on objective magnification)
Field of view	Typically up to 120 $\times$ 120 mm	Up to 200 mm	100 $\times$ 100 μm to 10 $\times$ 10 mm but can be extended by stitching	100 $\times$ 100 μm to 10 $\times$ 10 mm but can be extended by increased lateral sampling lens array objective
Measurable height range	Up to 20 μm	1 mm	8 mm (or limited by working distance of objective)	Limited by working distance of objective
Sample preparation	Little or none	None	None	None
Contact technique	Optional	Yes	No	No
Special surface requirements	STM - only conductive surfaces	Surface damage possible due to high forces	Needs correction for dissimilar materials and film coatings	Needs correction for dissimilar materials and film coatings
Scanning	Point by point	Point by point	Full field of view	Point by point
Full field dynamic motion of sample measurement	No	No	Yes	No

(Continued)

TABLE 15.1. (Continued)

	Atomic force/ scanning tunneling microscope	Stylus profiler	White light interferometric optical profiler	Confocal microscope
Through the glass measurement	Not possible	Not possible	Possible	Possible
Film thickness	Only if film has a step	Only if film has a step	Minimum 0.1 μm	Minimum 1 μm
Measurable optical properties of surface or film	Indirectly, through correlation with topography for example	no	yes	yes
Other measurable material properties	Numerous: adhesive, electric, magnetic, visco-elastic, elastic, ...	no	no	no

focusing lens until focus is achieved. Alternately, the signal may be collected during a scan through focus and then analyzed. The amount the lens is moved indicates the surface height at that data point. Either the optical head or the surface is scanned to generate a two- or three-dimensional height-profile map of the test surface. Special hardware is needed to sense the focus. A different group of methods for finding a surface profile that use a conventional microscope or a stereomicroscope is based purely on image processing of the collected images as the object is scanned through focus so as to find the best focus at each point.

Q2 The signal collected in optical profilers is often incorrectly called intensity; Palmer (Palmer, 1993) provides a clear discussion of the terms intensity versus irradiance. Intensity describes radiation emanating from source (watts/steradian) while irradiance describes signal collected by detector and is expressed in watts/area. We will use the term irradiance to describe the radiometric quantity detected by the detector.

15.3.1. Optical Focus Sensors

A simple method of determining focus has been implemented in profiling instruments developed by Brodman and Smilga (1987) and Breitmeier and Ahlers (1987). Illumination from a laser source is focused on the test surface, and the return is split at the optical axis into two parts using a prism. Each half of the beam is incident upon a split detector and the difference signal from each split detector is monitored. When the focusing lens is too high, the return beam focuses in front of the split detectors and causes a larger signal on the inner detectors; when the lens is too low, the larger

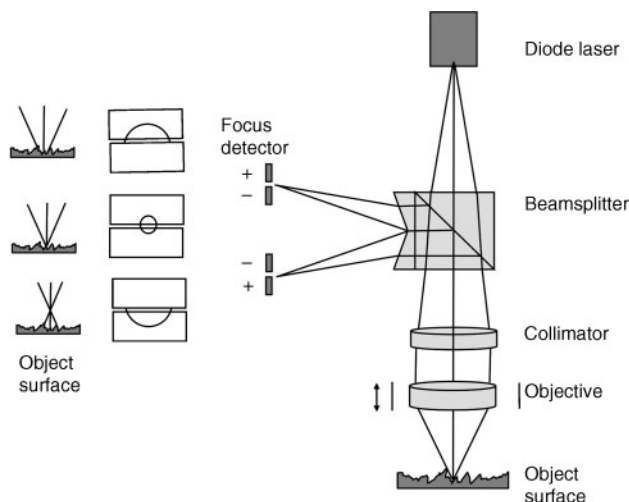


FIGURE 15.19. Schematics of a profilometer with an optical focus sensor.

signal is on the outer detectors. The sign of the difference in signal will determine which side of focus the test surface is on, and is used to generate a focus error signal which moves the focusing lens to the correct position. When the focusing lens is in the correct position, both the inner and outer detectors have equal signal and the difference signal is zero. Two sets of split detectors are used to account for variations in tilt of the test surface. A sensor of this type is shown schematically in Figure 15.19 (Brodman and Smilga 1987). Because the focus must be adjusted to null the signal at every sampled surface point, this type of profiler can take a few minutes to generate a three-dimensional surface profiler.

The lateral resolution of optical focus sensors is limited by the size of the focus spot at the test surface, usually 1.0 to 1.5 μm in diameter. The measured surface height at a given sample point will be the average height of the surface over the spot size. This means that the smallest measurable features are about 2 μm . The measurement area will depend upon the sampling interval and number of data points. Another limitation of this type of profiler is that the light reflected from the test surface must get back into the sensor. If there are steep slopes on the surface, the light may get scattered out of the instrument and the signal will be lost, causing inaccurate results when only the difference signal is monitored. The height resolution of this type of profiler is related to the focusing range and the time to obtain each point. If a large height range is being measured, the movement of the focusing lens needs to be coarser to keep the time per data point the same. Otherwise, finer focusing over larger height ranges will slow the measurement time considerably. Calibration of optical focus sensors is similar to that of stylus and SPM profilers. A traceable standard of approximately the same height or roughness as the test surface is measured and a scale factor is determined to apply to the surface profile data.

Auto-focusing techniques have been implemented in many fields, from high density storage applications to surveillance camera systems. Different optical setups

can also be used to measure the focus position. Astigmatic lenses (Cohen and Lightbody, 1984) and twin micro-Fresnel lenses (Shiono and Setsune, 1989) are two examples. Some profilometric techniques are based on focusing mechanisms developed for other applications like a CD player (Zhang and Cai, 1997; Bartoli et al., 2001). Two most common optical profilers based on a focusing principle are the confocal microscope and the white light interferometer. These will be described in Sections 15.3.2 and 15.5.

Conventional and stereoscopic microscopes without any special hardware can also map surface topographies after doing post-processing of the collected images, not single points, as the microscope scans through focus. Two of these methods are digital deconvolution and stereoscopic imaging.

Digital Deconvolution of Conventional Images. Images registered using a conventional microscope as it scans through focus are deconvolved using a theoretical or measured point spread function or through blind deconvolution. This method is used in medicine for reconstruction of 3D images from CT and MRI scans. Other methods are based on the measurement of local sharpness of the image (Nahm and Ryoo, 1998). These methods work best for objects with distinct lateral features, but these methods have difficulty resolving objects with smooth surfaces that have no lateral features.

Stereoscopic Imaging. Images registered using a stereoscopic microscope are analyzed by identifying the same features in both images and measuring the distance between features. Knowing the angles through which the two stereoscopic images are observed allows for the determination of the relative axial distances between different features on the object. Like deconvolution, this method works best for objects with distinct lateral features, but does not work well for objects with smooth surfaces or with periodic structures. Stereoscopic imaging can be used to image both large and small objects as long as the images are obtained from two different perspectives.

15.3.2. Confocal Microscopy

Like many interferometric methods confocal microscopy really took off with the development of image processing software and affordable, powerful lasers and computers. Back in 1961, Minsky patented modifications to a biological microscope that reduced the stray light in the system in order to improve the obtained image; however, only in the mid 1980s did the development of confocal microscopes to obtain non-invasive, three-dimensional data from biological specimens occur. Since this time, confocal systems have been an important measurement tool in the fields of cell biology, physiology, cytogenics and developmental biology (Pawley, 1995; Gu, 1996) and ophthalmology. The introduction of two-photon microscopy (Diaspro, 2002) in the late 1990s offered reduced photodamage and increased tissue penetration for better imaging. In recent years confocal microscopes have been adapted for the measurement of microsystems and material applications (Aguilar and Mendez, 1995; Schneider et al., 1997; Smith et al., 2000; Tiziani et al., 2000).

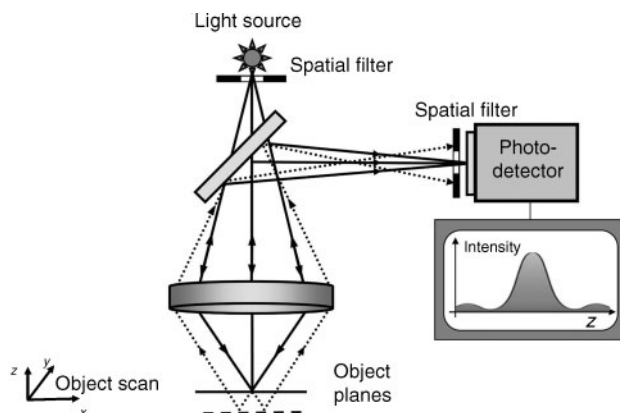


FIGURE 15.20. Depth discrimination in reflective confocal microscopy by eliminating out of focus light via confocal (pinholes) apertures.

Confocal microscopy sets itself apart from standard light microscopy through the use of confocal (pinhole) apertures that ensure only light at the point of focus on the test surface enters the detector. This elimination of out-of-focus and stray light and the resulting high resolution and high signal-to-noise images are the main advantages that recommend confocal microscopy. The classic setup of a confocal microscope places two small apertures in planes conjugate to the focal plane of the objective, one in front of the illuminating source and the other in front of the detector as shown in Figure 15.20.

In some systems, a spatially coherent light source, namely a laser, eliminates the need for a pinhole at the illumination source; however, in these systems speckle may become a problem. Because confocal microscopy is in principle a single point method, synchronized lateral scanning of the illumination and detection points is required.

Image Build Up. Point-by-point scanning of the illuminating and detecting pinholes typically in X-Y raster fashion results in a 2D irradiance image (single optical section) of a sample at a given focus plane. To build up a 3D irradiance image (multiple optical sections along the Z direction) either the sample or the objective lens or detector is scanned vertically such that each point on the sample surface passes through the focal plane of the microscope.

For each point on the sample passing through the focal plane of the microscope the collected irradiance (confocal) signal, which is also called the axial point spread function (PSF), falls off as the distance from focal plane increases. The width of this axial point spread function for a point object for aberration-free objectives with $NA < 0.5$ can be described by the simplified expression (Corle et al., 1986; Kino et al., 1988; Ho and Shao, 1991; Corle and Kino, 1996)

$$FWHM = \frac{0.9\lambda}{NA^2} \quad (15.2)$$

The width of the axial PSF depends on the numerical aperture (NA) of the objective and the wavelength. In reality the width of the axial response also depends on the tilt of the object and its shape, namely whether the object is a point or plane-like. The width of the spatial filter and the size of the detector also influence the axial response. Sheppard (Sheppard, 2003) provides a review of many issues in imaging confocal systems.

The signal collected at a single point on the object during a vertical scan is evaluated for maximum irradiance; maximum irradiance corresponds to the imaged point being in focus. In this way a confocal system for surface profiling works like a focal point detection system scanned over the test surface. The position of the axial point spread function can be more consistently determined if, for example, the center of gravity of the signal or the position of the polynomial fitted to the signal is determined instead of simply the position of maximum irradiance. The width of axial point spread function and the sampling rate also influence the consistency in determining the signal position and thus the vertical resolution. Better vertical resolution is achieved when the axial signal is narrower; because of this the best vertical resolution depends on NA and thus magnification of the objective. Vertical resolution for surface profiling is often defined as RMS (root mean square) of the difference measurement. The vertical resolution also determines the minimum step height that can be measured on a sample. For smooth surfaces the vertical resolution can be on the order of a few nm, but only for the highest magnification objectives. For lower magnification objectives the vertical resolution can be around 10–15 nm to microns. This vertical resolution often is called method's sensitivity.

Confocal microscopy is often used to measure the thickness of transparent layers in the process called optical slicing. Light penetrates the object, is reflected from the interfaces of the layers, and creates additional axial responses. Optical sectioning of confocal systems is commonly used to measure, for example, cells in biological applications and transparent coatings in the semiconductor industry. In cases like these, a different definition of vertical resolution is used, a definition that applies to the measurable optical thickness (Sheppard and Gu, 1992; Sheppard et al., 1994). This definition of axial vertical resolution is based on the vertical two-point resolution of the signal where the width of the axial signal determines the resolution, in this case the minimal measurable optical thickness. The vertical resolution of optical slicing can reach down to 1.5 μm for high NA objectives and is much larger than the vertical resolution related to the measurable step height. Figure 15.21 shows example of axial responses for transparent layer.

Much research has gone into improving vertical resolution mainly through the application of annular filters in the pupil (Sheppard and Gu, 1991; Martinez-Corral et al., 1995) to narrow the width of PSF in both directions as registered by a finite size detector. In order to enhance optical-sectioning capacity, some methods apply symmetrical defocusing of the point source and point (Sheppard and Hamilton, 1984; Ho and Shao, 1991; Kimura and Wilson, 1993). Axial apodization was proposed so as to improve vertical resolution by the application of destructive-interference apodizers, which provide an axial response with zero irradiance at the focal point (Martinez-Corral et al., 1998). Some have suggested using a

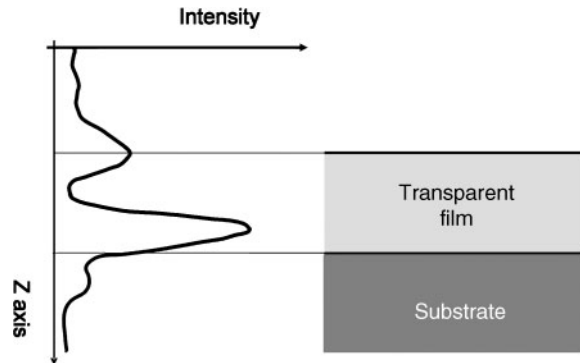


FIGURE 15.21. Schematic of axial response for transparent films in a confocal microscope. The position of the peak corresponding to the interface depends on the index of refraction of the material and appears to be at a shallower depth than the position of the interface, which reduces the capabilities of measuring thinner films. The width of the axial response depends on spherical and axial aberrations introduced by the film. The amplitude of the peaks depends on the ratio of the indices of refraction at the interfaces and thickness and dispersion of film.

phase conjugate mirror to improve vertical resolution (Uhlendorf et al., 1999). However, the one, practical solution for increased resolution still has yet to be developed.

Confocal System Modifications. Over the years a number of methods have been worked out to improve the speed of data acquisition; most employ variations on the confocal aperture. In 1967, Egger and Petran (and later, Petran et al., 1968; Xiao et al., 1988) introduced simultaneous illumination of the sample by many spots of light using an array of pinholes on a rotating disk. This Nipkow disk, invented by Paul Nipkow in 1884, produces images by rotating a disk with multiple pinhole apertures in front of the extended source. A second disk with a matching array of pinholes is placed in front of the detector; however, this method has a significant downside in that it reduces the amount of light at each sample point.

In 1996, Ichihara et al. showed that the amount of light in the system can be increased by up to 10 times placing by a disk with microlenses in front of the pinholes at the disk that is used at the illuminating beam. Pinholes may have different patterns and there may be even up to 20,000 pinholes on the disk with about 1000 of them illuminating the test object at a time. Speed measurements up to one frame/ms may be achieved using this method (Tanaami et al., 2002). Tiziani et al. (2000) suggested a simpler system where pinholes in the Nipkow disk are replaced by the microlenses itself, although this system has a lower lateral resolution. Such system is shown in Figure 15.22.

Some systems use a scanning slit (Wilson, 1990) instead of a pinhole. A slit aperture represents an alternate geometry to the array of pinholes. In the slit-scan system, multiple detectors are required along the length of the slit, and lateral scanning is necessary only in the direction perpendicular to the slit, which increases the speed of image acquisition (Neil et al., 1997). However, with slit scanning, the

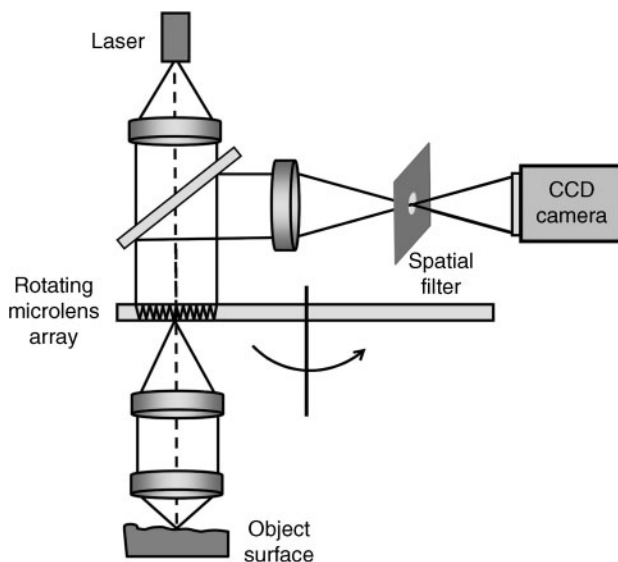


FIGURE 15.22. Confocal microscope with microlens array on Nipkow disk.

width of axial responses is wider than for single point scanning systems, and the vertical resolution is reduced for the given numerical aperture objective.

Yet another method to speed up measurement time is to simultaneously project an equally spaced multiple slit or grid pattern. For these kinds of projected patterns, however, the width of the axial signal with defocus will depend not only on the NA of the objective but also on the spatial frequency of imaged pattern. The fundamental difficulty with this method is the residual unwanted grid pattern in the image. The grid pattern can be removed if the projected pattern is moved in a simple saw-tooth fashion synchronized to the camera frame rate such that any three successive camera images corresponded to a spatial shift of one third of a period in the position of the projected image of the grid. The grid pattern image, because of its periodicity, can be processed also in the Fourier domain.

In the first systems that projected a grid pattern, this pattern was imprinted on a glass plate and laterally shifted by a PZT shifter. Nowadays, the illumination beam can be reflected off a digital micromirror array (DMD made by Texas Instruments) that configures the grid pattern (Hanley et al., 2000), or a polarized illumination beam can be reflected off of a ferroelectric liquid crystal (FLC) (Smith et al., 2000) that configures the pattern (slits or single points) projected onto the sample surface. Each system setup has to match the microdisplay lines and the rows of the CCD pixels. The lateral scanning of the pattern is done by displaying a series of patterns on a microdisplay without the use of a PZT.

If good vertical resolution is a requirement from the confocal profilometer, a high numerical objective needs to be used. The downside of the high NA objective is its small field size. Tiziani and Uhde (1994b) proposed the use of a microlens array in

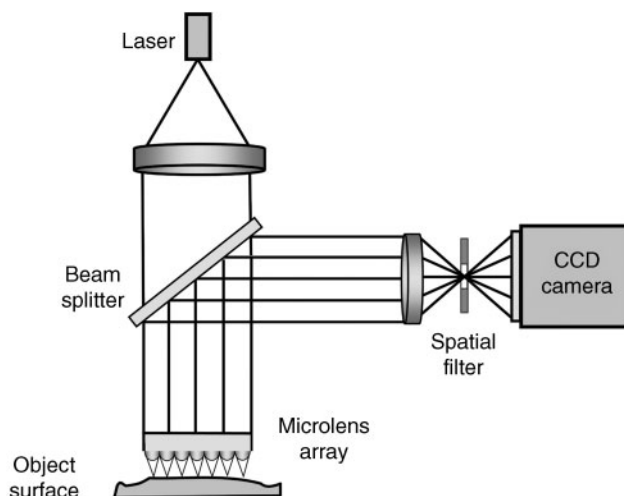


FIGURE 15.23. Wide field confocal microscope with microlens array in place of the objective.

Q3

place of the objective as shown in Figure 15.23. This array would allow for the measurement of larger fields; the fields would be determined by the size of the array while each individual microlens would still maintain a high NA. The focal lengths of the individual lenses could be adjusted to the shape of the object in order to decrease the scanning range and further speed up the (Tiziani et al., 2000). The system with microlenses in place of the objectives is a bit different than the typical confocal microscope because the light reflected from each object point while being in the focal plane of that microlens is focused by the lens onto a pinhole, which plays the role of a spatial filter. The pupils of the microlenses are imaged onto the camera rather than the image point as in typical confocal setups. For this system a vertical resolution of 50 nm was achieved for an objective with an $NA = 0.3$.

Chromatic Confocal Microscopy. The chromatic confocal microscope was developed to circumvent the necessity in confocal systems of the vertical scan in order to ascertain relative object height position. Rather than a vertical scan, a chromatic confocal microscope employs an objective with a longitudinal chromatic aberration that creates a different focus position for each different wavelength. This idea was first devised by Molesini in 1984 (Molesini et al., 1984) and then adapted to confocal microscopes by Browne et al in 1992; then, others followed (Tiziani and Uhde, 1994a; Dobson et al., 1997; Cha et al., 2000; Lin et al., 1998; Ruprecht et al., 2004). Only the wavelength, whose focus position coincides with object position, is reflected back to the system. For this reason these systems are also called wavelength-to-depth encoding setups. A spectrometer, in place of the CCD camera, detects the wavelength value. Instantaneous measurement of the object focus position by measuring the power spectrum replaces the need for any scanning mechanism

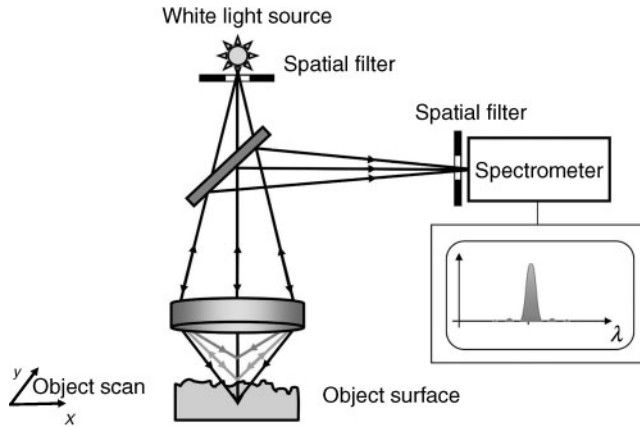


FIGURE 15.24. Schematic of chromatic confocal microscope.

and makes the measurement process much faster. Schematic of chromatic confocal microscope is shown in Figure 15.24.

These systems usually use broadband (i.e., white light) sources and a spectrometer, but some systems employ a wavelength tunable source and a CCD camera (Mehta et al., 2002) or white light source and color CCD camera (Tiziani et al., 2000). The wavelength for which the maximum power is detected is encoded to the depth of the object. A drawback to this technique is that the measurable maximum depth depends on the chromatic aberration of the lens and the source spectrum. The diffractive lenses that are used in confocal systems (Dobson et al., 1997) can provide stronger longitudinal dispersion, which is material independent and can be characterized analytically in contrast to refractive lenses. The focal length of the diffractive lens for a given wavelength λ follows the linear dispersion

$$f(\lambda) \approx 2f(\lambda_d) - f(\lambda_d)/\lambda_d \quad (15.3)$$

if $\lambda - \lambda_d$ is much less than the design wavelength λ_d . For lower NA this range can be even 2–3 mm, and for higher NA (i.e., 0.75) this range can be of the order of 10 μm . Shi (2004) proposed the use of supercontinuum light which has a high spatial coherence and very wide spectrum, which results in wider measurable object depth and no speckle noise. Supercontinuum light may be a solution to the light efficiency problem in confocal systems. Light efficiency may be also improved by using an extended detection pinhole (Ruprecht, 2004).

Similarly as in a conventional confocal system in order to avoid mechanical lateral scanning of the sample or objective, slit (Lin et al., 1998), microlens (also diffractive) array (Tiziani et al., 2000) can be applied, or a dynamically configurable micromirror like a digital micromirror device (DMD) (Cha et al., 2000), and a liquid crystal display can be used, which serve as a scanning point source (pattern) and detection pinhole.

15.4. INTERFEROMETRIC OPTICAL PROFILERS

Interferometric optical profilers are based on standard microscopes where an interferometer built into the objective replaces the standard objective. The interference signal obtained with these objectives is analyzed to provide quantitative data about an object being measured. Interferometric optical profilers generally record a number of frames of data in order to calculate surface heights at each detector point. During measurement the interference signal is varied by changing the optical path between the object and reference beams; this varying is usually accomplished using phase-shifting or vertical scanning techniques that move the objective relative to the test surface using a piezoelectric transducer or motor scanner. Some methods avoid mechanical scanning by using the spectral properties of the light source; wavelength scanning and wavelength dispersing are two such methods. Which method used for a particular analysis depends on the type of object to be measured.

15.4.1. Common Features

The four interferometric objective setups that are typically used are based on the Michelson, Mirau, Linnik, and Fizeau interferometers. Schematics of these interferometric objectives are shown in Figure 15.25. A number of factors help determine the choice of best objective for a particular measurement. These factors include the level of magnification or more precisely the numerical aperture required to both resolve the features and measure slopes and heights on the sample. At the same time a

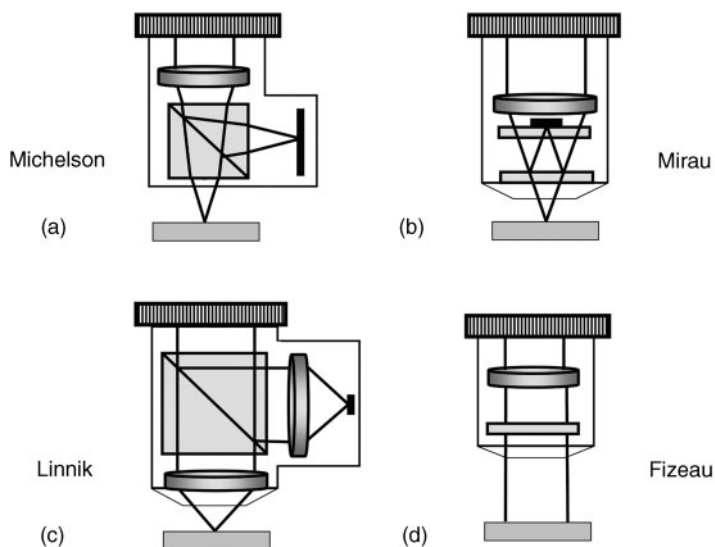


FIGURE 15.25. Schematics of interferometric objectives: (a) Michelson, (b) Mirau, (c) Linnik, and (d) Fizeau.

magnification level that measures the entire area of interest on a sample needs to be chosen. This section first describes various types of interferometric objectives and then examines the characteristics of different objective setups that determine which is best suited to a particular application.

Types of Interferometric Objectives. The design of the interferometric objective is constrained by the mechanical limitations of the system. The four typical objectives differ in the ways that the beam is split into reference and object beams. In all but the Fizeau objective, the reference mirror is placed at the best focus of the objective to obtain best contrast fringes when the sample is in focus. In order to obtain best focus position, the object first needs to be placed in focus, and then the reference mirror is moved to a position for which the best contrast fringes are obtained; this position also corresponds to best focus position. The best contrast fringes correspond to the zero optical path difference (OPD) between the reference mirror and the object position in the arms of the interferometer.

Michelson interferometers (Fig. 15.25(a)) are comprised of an objective, a beamsplitter and a separate reference surface. The microscope objective must have a long working distance to fit the beamsplitter in between the objective and the surface. Because of this, Michelson interferometers are only used with low-magnification objectives having low numerical apertures and long working distances.

Mirau interferometers (Fig. 15.25(b)) contain two small glass plates between the objective and the test surface. One plate contains a small reflective spot that acts as the reference surface, and the other plate is coated on one side to act as a beamsplitter. The plate with the reference spot also acts as a compensating plate. These interferometers are used for midrange magnification objectives where not enough space exists to insert a beamsplitter cube so as to create a Michelson interferometer. Mirau setups are not very useful at magnifications of less than about 10X because at these lower magnifications the reference spot obscures too much of the aperture. The reference spot has to be larger than the field of view of the objective since it is a surface conjugate to the best focus plane of the object. For magnifications above 50X, the working distance of the objective is too short to place either a beamsplitter cube or plates underneath it.

The Linnik system (Fig. 15.25(c)) allows an interferometer to be set up for any magnification objective from two identical bright field objectives. However, these interferometers are also very difficult to adjust, and thus their commercial use is rather limited. Linnik systems are often used with a high-magnification objective that has a short working distance. A Linnik setup is comprised of a beamsplitter, two matched microscope objectives and a reference mirror. The entire reference arm provides path-length matching in order to obtain white-light fringes. The two objectives need to be matched with a beamsplitter to provide a wavefront with minimum aberration and maximum fringe contrast.

The three objectives discussed above are all variations of the Michelson interferometer and all are equal-path interferometers.

The Fizeau interferometer (Fig. 15.25(d)) is an unequal-path interferometer that requires a source with a long coherence length; this setup is well suited for

monochromatic or spectral interferometry, but not for white light interferometry. The objective provides a collimated beam on the test surface while imaging the test surface. Since interference fringes will be visible over a large depth of field when a long coherence length source is used, care must be taken to focus on the test surface. Spurious fringes created by Fizeau cavities have to be watched for while analyzing fringes. Fizeau objectives can be used with a large range of magnifications; however, there must be enough room to place the reference surface between the objective and the test surface.

With all of the interferometers except the Fizeau, there is a cone of light incident upon the test surface, and all of these objectives except the Fizeau can be adjusted to obtain white-light fringes.

Depending on the type of object to be measured different illumination schemes may need to be implemented. For measurements of optically smooth surfaces typically instruments based on phase detection in monochromatic illumination are used. The analysis of monochromatic fringes is described in the chapter on Phase Shifting Interferometry. For objects with larger discontinuities, roughness and heights, alternate illumination schemes and fringe analyses need to be applied. Techniques that extend the measurement range of the systems form the basis of this chapter, but first we describe the properties of the objectives and the features of a sample that can be measured with a given objective setup.

Matching Interferometric Objectives with Object Parameters. When using an optical profiler the choice of interferometric objective for a particular measurement first requires determining a number of parameters about the sample and the features to be resolved. Decisions need to be made about the smallest lateral features, the maximum height range and maximum slopes to be measured as well as the area to be measured. While magnification of the objective (plus intermediate optics) and size of CCD camera determine the measurable object area, the NA of the objective and the type of illumination determine which features on the object can be measured. Some of properties of the objectives discussed below can also be applied to the objectives used in confocal profilometry.

Lateral Resolution. In order to determine which lateral feature on a sample can be resolved, the lateral resolution of the system first needs to be known. The lateral resolution of a system that is based on a microscope depends mainly on the optical resolution of objective used. Only systems with low magnification objectives may be limited by detector sampling. Optical resolution depends only on the wavelength and the numerical aperture of the microscope objective. Sparrow and Rayleigh cite slightly different criteria (see Born and Wolf (1999)).

$$\text{Sparrow optical resolution criteria} = \frac{0.5\lambda}{\text{NA}} \quad (15.4)$$

$$\text{Rayleigh optical resolution criteria} = \frac{0.6\lambda}{\text{NA}} \quad (15.5)$$

TABLE 15.2. Characteristics of objectives for following assumptions: wavelength 600 nm, Sparrow criterion for optical resolution calculations, sampling interval of camera 6.8 μm , and number of camera pixels in one direction, 1024.

Interferometer type	Michelson		Mirau		Linnik	
	2.5	5	10	20	50	100
Magnification (X)						
Numerical aperture	0.075	0.13	0.3	0.4	0.55	0.9
Optical resolution (μm)	4.00	2.31	1.00	0.75	0.55	0.33
Depth of field (μm)	106	35	6	3.5	1.6	0.35
Lateral sampling interval (μm)	2.72	1.36	0.68	0.34	0.17	0.068
Field of view area (μm)	2785	1393	696	348	174	70

These criteria apply for an incoherent system imaging two radiating points as an object, and they are a good general rule of thumb. However, a microscope is (at best) a partially coherent system and objects may take different forms. Modified criteria do exist that consider the coherence state of the system and the type of test sample, but in practice the Sparrow criterion is a good approximation for an optical microscope. It is worth remembering that registering an image with a CCD camera requires at least three pixels in order to resolve an image of two points. Optical resolution and lateral sampling for a typical interference microscope are shown in Table 15.2.

Measurable Heights Range. A test surface can be measured only when fringes are visible on its surface. When monochromatic, multiple wavelength or spectral techniques are used where the object practically stays at one focus position, fringes have to be visible over the whole height range of the object. This height range of the test surface must be within the depth of field of the interferometric objective. In addition, when the illuminating source has some wavelength bandwidth $\Delta\lambda$, then the test surface must also be within the coherence length of the source.

The depth of field of the objective depends upon the NA and the wavelength λ of illumination; it is defined by (see Benford (1966))

$$\text{Depth of field} = \lambda \frac{\sqrt{1 - (\text{NA})^2}}{(\text{NA})^2} \quad (15.6)$$

The coherence length (this is an approximation) of the source can be determined from central wavelength λ of the source and its bandwidth $\Delta\lambda$:

$$\text{Coherence length} = \frac{\lambda^2}{\Delta\lambda} \quad (15.7)$$

The measurable height of the object is determined by the smaller of these two numbers, namely the coherence length of the source and the depth of field of the interferometric objective. Other criteria, which are dependent on the measurement method used, may further limit the measurable height range.

The measurable height range for methods in which the object is scanned through focus such as with confocal or white light interference profilers is limited by the scanning range and the working distance of the objective.

Measurable Slopes. The maximum of the measurable slope of the sample also depends on the NA of the objective. If light reflected from a sample with a high slope is not gathered by the objective, the slope can not be measured. A common assumption holds that slopes with a maximum 0.75NA return sufficient light to be measurable as long as fringes with sufficient contrast are created. For objects with rough surfaces higher slopes can be measured since diffuse surfaces allow some light to travel back to the objective.

Table 15.2 gives the optical resolution predicted by the Sparrow criterion for 600 nm wavelength of the source along with the depth of a single image at the object plane (the coherence length or depth of field, whichever is smaller), lateral sampling interval on the test surface, and field of view across the test surface. In summary, objectives of lower numerical aperture can measure samples of larger height ranges and larger field of views, but they cannot resolve high slopes and small lateral features. Good knowledge of object features to be measured, on the contrary of objectives and measurement techniques capabilities, is needed in order to obtain required measurement result.

Interference Fringes. All of these interference objectives create an interference pattern that can be observed by the CCD camera. We will now consider the interference signal as registered by a single point x, y ; however, for simplicity these coordinates will be omitted in all equations. For a single wavelength and a single point source on axis (a spatially and temporally coherent source) and thus a single angle of beam incidence, the interference signal can in its most general form be described as

$$I(k, z, \theta) = I_R(k) + I_O(k) + 2\sqrt{I_R(k)I_O(k)} \cos(2k(h - z) \cos(\theta) + \phi(k)) \quad (15.8)$$

where $k = 2\pi/\lambda$ is the wave number for a source wavelength λ , and I_R and I_O are the detected irradiances reflected from the reference mirror and the object, respectively. I_R and I_O depend on the reflectivity of the object and the reference mirror, the transmissivity of the optical system, camera sensitivity and the spectrum of the source.

Optical Path Difference. The optical path difference (OPD) between interfering beams is described as the optical phase under the cosine from Eq. (15.8) in the following form:

$$\phi = (2k(h - z) \cos(\theta) + \phi(k)) \quad (15.9)$$

where $h - z$ is the geometrical path difference between a point on the object and a corresponding point on the reference mirror, h represents object height, and $\cos \theta$ is the direction cosine of the beam's incident angle onto the object. The remaining

phase term $\phi(k)$ represents the phase change on reflection introduced by the material of the object; the phase term may also contain both the statistical phase term introduced by speckles and the phase offset due to the dispersion of the instrument, which typically is assumed to be zero.

When $h - z$ equals zero, the object and reference beam are traveling the same total optical path length. Thus, this point corresponds to the zero optical path difference (zero OPD) between the beams. The objective is typically set so that the zero OPD position corresponds to the object and reference mirror position being in focus.

In general, the OPD encoded in the fringes at each point varies with two parameters; the geometrical path difference $h - z$, and the wave number k . These parameters can be used to vary the OPD in a controlled way, and they are the critical variables that distinguish the various methods for creating and analyzing fringes, namely phase shifting, white light, wavelength scanning, spectrally resolved white light. Other methods for changing the OPD, which are not described here, are based on modifying the direction cosine $\cos \theta$ (Duan et al., 2006) and the refractive index in the optical path (Zelenka and Varner, 1969; Ei-Ghandoor, 1997; Hung et al., 2000). For influence of range of direction cosines as determined by NA of the objective see Section 15.4.1.4.

Fringe Visibility. Interference fringes as observed by each detector pixel (Eq. (15.8)) can be described in a simpler form as

$$I = I'(1 + \gamma \cos(\varphi)) \quad (15.10)$$

where I' is dc irradiance and γ is the fringe visibility (also called modulation, contrast or amplitude). Good fringe visibility is required for good measurement. To obtain good fringe visibility, the irradiances I_R and I_O need to be as equal as possible (see Eq. (15.8)). For this reason objectives may have reference mirrors with different reflectivities to match the test sample's reflectivity. In reality the fringe visibility is a more complicated function that decreases as the OPD increases and is affected by the temporal and spatial coherence of the source (Born and Wolf, 1999; Hariharan, 2005), thus by the wavelength bandwidth and size of the source. The apparent size of the source is in turn determined by the NA of the objective. Thus, the fringe visibility may vary over different height ranges of the object, and it is this fringe visibility that determines the maximum measurable range.

Influence of the Numerical Aperture of the Objective on Fringes. In addition to the effects of the NA of the objective on measurable height range, the observed wavelength of the fringes can differ slightly from the source. For high NA objectives the range of the incident angle of beam onto the object can affect the interference signal. Thus, a correction factor for the central wavelength (central wave number k_c) of the source must be used in order to get accurate height information (Bruce and Thornton, 1956; Gates, 1956; Tolomon, 1956; Ingelstam, 1960; Biegen and Smythe, 1988; Creath, 1989; Schulz and Elssner, 1991; Sheppard and Larkin, 1995; Dubois et al., 2000; Wan, Schmit and Novak, 2004). While for low NA objectives like

NA = 0.1 the correction factor for the wavelength is about 1.0025 and can be neglected, for objectives with NA = 0.5 the correction factor rises to about 1.07 and for NA = 0.9 the correction factor is larger than 1.3. Since these interference microscope systems are complicated to model, most corrections are accomplished by using a traceable step-height standard to calibrate to correct scaling factor.

Limitations of Single-Wavelength Interferometric Optical Profilers. At first interferometric optical profilers for full-field measurement of object shape were based on single wavelength phase shifting interferometry (PSI) (for details see chapter on Phase Shifting Interferometry). These profilers delivered results with low noise, and smooth optical surfaces could be measured with very high precision, on the order of angstroms, while collecting only a few frames of data. However, PSI techniques were limited because they could only resolve smooth objects (optical roughness up to approximately $\lambda/30$) with height discontinuities less than $\lambda/4$. During PSI measurement the optical path difference is changed in a few steps of a quarter of the fringe (90° or $\pi/2$), typically by having the PZT shift either the reference mirror or the object. The interference signal is analyzed at each point on the object using one of the many algorithms that were developed. Algorithms that compensate well for the nonlinear motion of the PZT use eight frames of data (Schmit and Creath, 1996) to calculate the optical path difference between beams over the measured area:

$$\varphi = \arctan\left(\frac{5I_2 - 15I_4 + 11I_6 - 2I_8}{I_1 - 11I_3 + 15I_5 - 5I_7}\right) \quad (15.11)$$

where irradiances $I_1, I_2, \dots, I_8$ are collected from single points in consecutive data frames.

Because PSI algorithms use an arctan (precisely $\arctan 2(N,D)$) function, they can only determine the phase within modulo 2π , which means that only the fractional fringe order (fractional interference number) is determined and the relative fringe order has to be assigned during the spatial unwrapping procedure. The spatial unwrapping procedure assumes that the fringe order can not change from point to point by more than half an order (in phase terms by no more than π). The unwrapped phase has to be converted from radian to height units by means of a simple relation. For the object measured in reflection at normal incidence 2π corresponds to $\lambda/2$.

$$h = \frac{\lambda}{2} \times \frac{\varphi}{2\pi} \quad (15.12)$$

Thus, if the object has a height discontinuity larger than $\lambda/4$, then the fringe order will not be properly assigned and the object will not be measured correctly. This is called a 2π ambiguity problem.

Figure 15.26(a) shows interference fringes obtained in monochromatic illumination for a reflective binary grating. We can see that in this figure that it is not possible to determine the relative fringe order on both sides of the grating's discontinuities. Figure 15.26b shows fringes obtained for the same object using white light

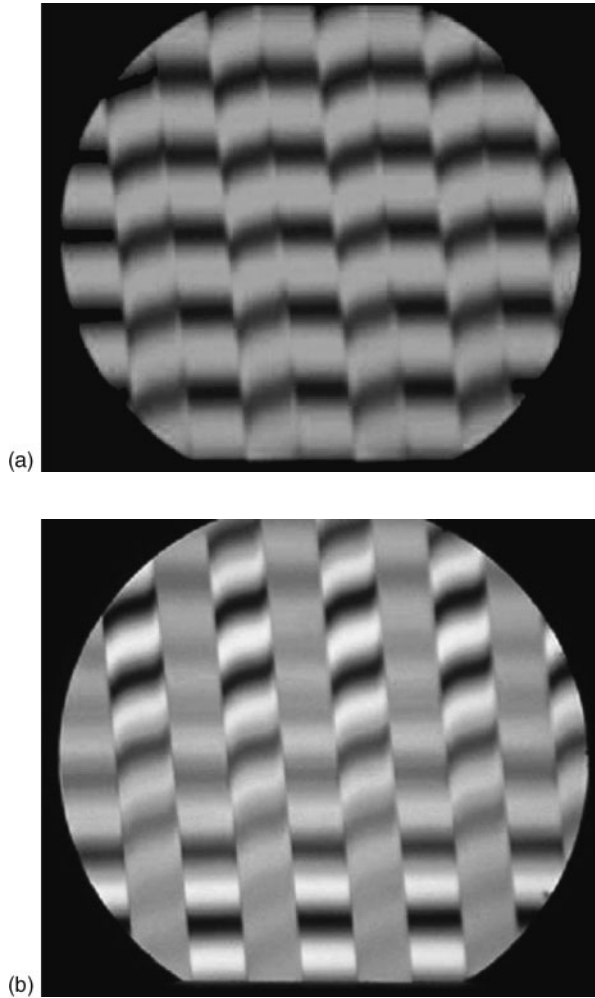


FIGURE 15.26. Fringes for object in form of 3D binary grating in (a) quasi-monochromatic and (b) white light illumination.

illumination. From this figure we see that the zero order fringe can be easily determined on both sides of the grating's discontinuities, which solves the problem of 2π ambiguity.

We will next discuss interferometric methods that solve the 2π ambiguity. These methods can be used to measure smooth and rough objects with step discontinuities up to a few mm. Sometimes even smooth objects without discontinuities cannot be measured correctly; this problem occurs when the slope of the object is so large that height difference between consecutive points is larger than $\lambda/4$, which corresponds to sampling the fringe with less than four pixels. Higher slopes may even not be able to be resolved by the detector.

15.5. TWO WAVELENGTH AND MULTIPLE WAVELENGTH TECHNIQUES

As mentioned previously, single wavelength interferometry has difficulty obtaining accurate measurements for objects that have high slopes. This difficulty occurs because the generated fringes are so dense that they are not able to be resolved by the detector. Two-wavelength techniques provide a way to expand the capabilities of single wavelength interferometry by creating fringes at a longer synthesized wavelength that corresponds to fringes that would be created if a long wavelength source were used (i.e., infrared source). Figure 12.61 in Chapter 12 shows fringes that are unresolvable in places using a single, short wavelength (a) and then fringes at different synthetic (effective) wavelengths (b–f). Fringes at the synthesized wavelength itself are analyzed rather than fringes at the two individual wavelengths that comprise the synthesized wavelength. The single synthetic wavelength is generated by using two short visible wavelengths simultaneously, and an interferogram is acquired that is identical to the one that would be obtained if a single longer wavelength source were used. This technique enables a wider range of surfaces to be unambiguously and accurately measured without use of expensive long wavelength sources and detectors for these wavelengths. These observed fringes of longer effective wavelength are basically moiré fringes, which are described in Chapter 16. Interferometric techniques that employ two or more wavelengths have been described by many authors over the last 110 years (Hildebrand and Haines, 1967; Heflinger and Wuerker, 1969; Wyant, 1971; Polhemus, 1973; Benoit, 1898). Fringes of long effective wavelength were often used in two wavelength holography for aspherics measurement (Wyant, 1971), but they can also be used to measure rough surfaces.

15.5.1. Two-wavelength Phase Measurement

As long as the fringes generated at each wavelength can be resolved by the detection system, two measurement wavelengths can be used with phase-shifting techniques (Cheng and Wyant, 1984; Wyant, et al., 1984; Creath et al., 1985; Fercher et al., 1985; Wyant and Creath, 1989; Creath and Wyant, 1986; Creath and Wyant, 1986a;.) These techniques are used to measure objects with height discontinuities larger than ($\lambda/4$ at either of single wavelengths. By using the information from a second wavelength, the height range of the measurement can be significantly increased.

A two-wavelength phase measurement is performed by first taking data at one wavelength while shifting the phase in appropriate amount for that wavelength. The modulo 2π phase is then calculated for this first wavelength. The illumination wavelength is then changed, and data are taken at the second wavelength with the appropriate phase shifts; the modulo 2π phase is then calculated for this second wavelength. These two modulo 2π phase measurements can then be combined to produce a modulo 2π phase corresponding to a long synthetic wavelength, which is

the beat between the two measured wavelengths. The phase corresponding to the new synthetic wavelength can be described as

$$\varphi_e = \varphi_1 - \varphi_2 = 2\pi\text{OPD}\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) = \frac{2\pi\text{OPD}}{\lambda_e} \quad (15.13)$$

where φ_1 and φ_2 are phases at wavelengths λ_1 and λ_2 ($\lambda_2 > \lambda_1$), and the effective wavelength, which then is described as

$$\lambda_e = \frac{\lambda_2\lambda_1}{\lambda_2 - \lambda_1} \quad (15.14)$$

Once the fractional fringe at the effective wavelength is determined, the fractional order is assigned by using the same spatial phase unwrapping procedures used with single wavelength techniques. Now, the new fringe order corresponds to the effective wavelength, and a measurement can be done correctly over larger height discontinuities. The effective wavelength in two wavelength interferometry is symbolically presented in Figure 15.27.

An alternate method for calculating the effective wavelength phase is to take all the frames of data for both wavelengths and then calculate the phase difference between individual wavelength phases instead of first calculating each individual wavelength phase and then subtracting it. In this method the effective wavelength phase can be calculated directly from the irradiance data. This calculation can be written as

$$\phi_e = \tan^{-1} \left[\frac{\sin(\phi_1 - \phi_2)}{\cos(\phi_1 - \phi_2)} \right] = \tan^{-1} \left[\frac{\sin \phi_1 \cos \phi_2 - \cos \phi_1 \sin \phi_2}{\cos \phi_1 \cos \phi_2 + \sin \phi_1 \sin \phi_2} \right] \quad (15.15)$$

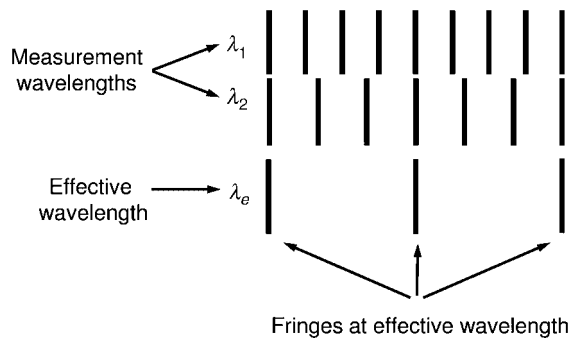


FIGURE 15.27. Beat wavelength, called effective or synthetic wavelength, for two-wavelength interferometry.

In general any PSI algorithm can be implemented to two wavelength interferometry. If a PSI algorithm is described by numerator N and denominator D , the phase is expressed as

$$\phi_i = \tan^{-1} \left[\frac{\sin \phi_i}{\cos \phi_i} \right] = \tan^{-1} \left[\frac{N_i}{D_i} \right] \quad (15.16)$$

and then the effective wavelength phase can be obtained from

$$\phi_e = \tan^{-1} \left[\frac{\sin(\phi_1 - \phi_2)}{\cos(\phi_1 - \phi_2)} \right] = \tan^{-1} \left[\frac{N_1 D_2 - D_1 N_2}{D_1 D_2 + N_1 N_2} \right] \quad (15.17)$$

The required phase shift between frames typically equals 90° . In order to realize a 90° phase shift for each wavelength, when using a PZT phase shifter, the PZT needs to shift by different distances that correspond to each wavelength used. However, if a polarization interferometer is used, then an achromatic phase shifter (Hariharan, 1996) introduces the proper 90° phase shift for the selected wavelengths (see also Section 8.9). When a system uses a PZT phase shifter that is calibrated only to a single wavelength, for frame sets with phase shifts different than 90° , a phase calculation based on least-square method (Kim et al., 1997) can be used. An even better solution has the phase being calculated using an algorithm that is insensitive to large phase shift miscalibrations (Carré, 1966). The phase shift can also be introduced by a frequency change in the laser diodes (Ishii and Onodera, 1991).

Table 12.6 in Chapter 12 lists the values of λ_e that can be obtained using various pairs of wavelengths from an argon ion and a helium–neon laser. By using a dye laser, a large range of equivalent wavelengths can be obtained (Schmidt and Fercher, 1971). Tunable helium–neon lasers with four or five distinct wavelengths ranging from green to red are also available (Wyant, 1971). A range of distinct wavelengths can be obtained with tunable and compact laser diodes for which the wavelength stability needs to be considered (de Groot and Kishner, 1991). In interference microscopes a white light source followed by narrowband spectral filters (Creath and Wyant 1986b) that are typically based on different laser lines are used.

de Groot (1994) has shown that if the fractional phases at single and effective wavelengths are known, the dynamic range does not need to be limited by the effective wavelength in two wavelength interferometry; rather, through analytical manipulations the wavelength can be extended to multiples of the effective wavelength where the multiplier N equals

$$N = \left\lceil \text{int} \left[\frac{1}{\lambda_e/\lambda_1 - \text{int}(\lambda_e/\lambda_1)} \right] \right\rceil \quad (15.18)$$

For example, for green and red spectral emissions and a red wavelength of 644 nm, the effective wavelength equals $2.42 \mu\text{m}$, but with the calculated multiplier it can be extended to $10 \mu\text{m}$. However, this technique is limited by long calculation times and

Q2

noise in the measurement. Because of the measurement noise, an approach described in the next section was developed that uses the second wavelength measurement only to correct a single wavelength measurement.

Correction of single wavelengths measurements. The noise in a two-wavelength measurement is proportional to the length of the wavelength used. For example, if there is an RMS measurement noise of $0.01\text{ }\mu\text{m}$ at $\lambda = 0.5\text{ }\mu\text{m}$, there will be an RMS noise of $0.1\text{ }\mu\text{m}$ with an effective wavelength of $\lambda_e = 5\text{ }\mu\text{m}$. A two-wavelength measurement can be used to correct the phase ambiguities in the modulo 2π single wavelength phase to provide a measurement with visible wavelength precision and extended height range (Creath, 1986). This precision is achieved by comparing a scaled version of the long effective wavelength phase with the single wavelength phase. The number of 2π s to add to the single wavelength data are determined by looking at the height changes in the scaled effective phase. This correction works well for relatively smooth data. If the noise in the scaled effective phase is greater than $\pm\lambda/4$ between adjacent pixels at the single wavelength then unwanted 2π jumps occur in the corrected data.

15.5.2. Multiple-Wavelength phase measurement

Two-wavelength techniques can be extended to multiple wavelengths in order to correct single wavelength data (Cheng and Wyant, 1985; Dandliker, Zimmermann and Frosio, 1992; de Groot, 1991; Decker et al., 2003; Towers et al., 2003). A number of wavelengths are specifically chosen so that a series of effective wavelengths are produced that are proportionally spaced from the single wavelength up to the wavelength necessary to measure the test object. A rule of thumb for good measurements is to keep the ratio between the longer wavelength and the wavelength being corrected between a factor of five and ten, and this ratio is limited depending on the level of phase noise in the measurements. For situations with low phase noise, the ratio can be made larger, and a reduced number of wavelengths are required to span the range between the shortest measurement wavelength and the desired measurement range.

An example of a $13\text{-}\mu\text{m}$ step measured using single, two-wavelength, and multiple-wavelength techniques is shown in Figure 15.28. These measurements were taken using an interferometric optical microscope with phase-shifting capability. Figure 15.28(a) shows the step measured at a wavelength of 657 nm . A two-wavelength measurement is shown in Figure 15.28(b) where the measurement wavelengths are 657 nm and 651 nm producing an effective wavelength of $64\text{ }\mu\text{m}$. The difference between two consecutive measurements using two wavelengths is shown in Figure 15.28(c) where the RMS is 7.13 nm . This means that the measurement is repeatable to within $\lambda_e/9000$ at the effective wavelength. Using the data from the 651 nm measurement to correct the phase data taken at 657 nm , the result given in Figure 15.28(d) shows uncertainties of 2π , which are caused by noise in the single wavelength measurement. If three measurement wavelengths (657 nm , 651 nm , and 601 nm) are used, the corrected measurement at 657 nm shown in Figure 15.28(e) is

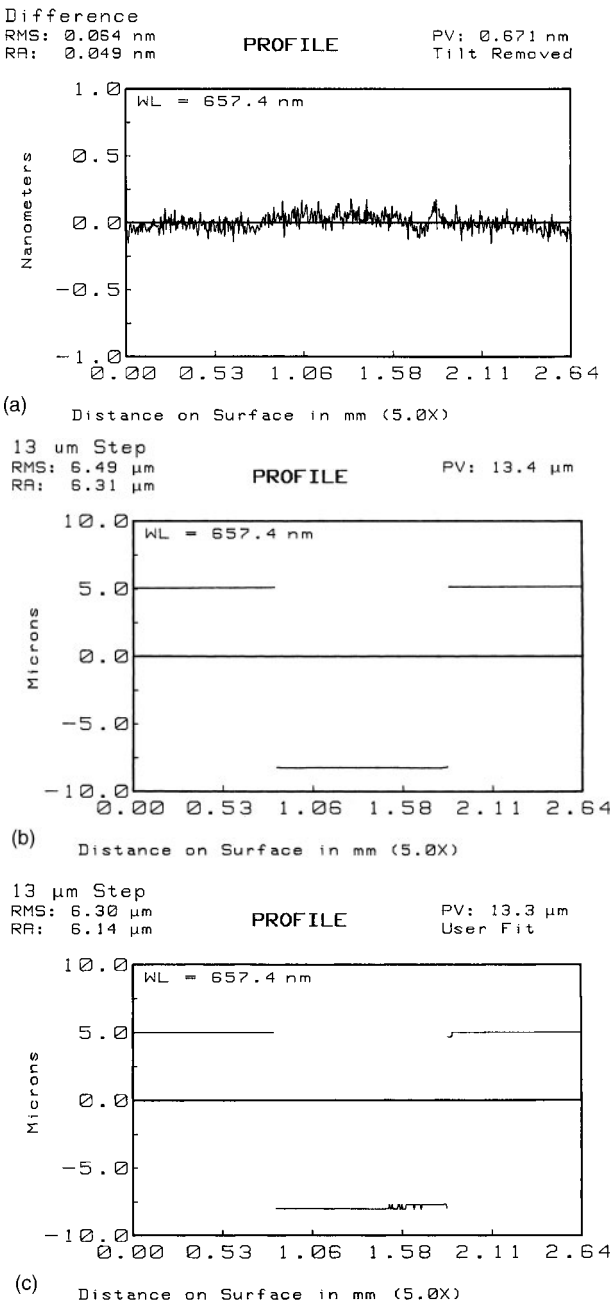
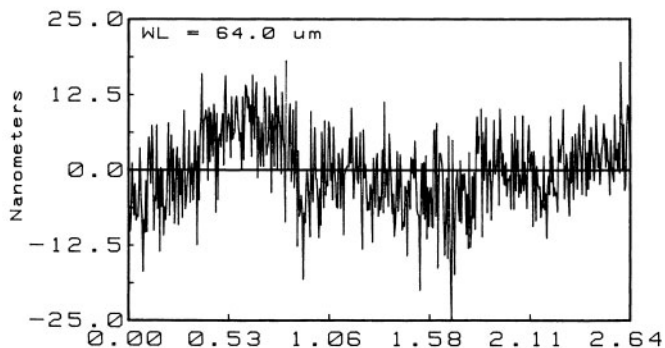


FIGURE 15.28. Measurement of 13 μ m step using multiple wavelength interferometry: (a) 657 nm, (b) two-wavelength measurement using 657 and 651 nm with $\lambda_e = 64 \mu$ m , (c) difference of consecutive two-wavelength measurements, (d) 657 nm data corrected using two-wavelength measurement, (e) three-wavelength using 657, 651, and 601 nm, and (f) difference of consecutive three-wavelength measurements.

Difference
 RMS: 7.13 nm
 RA: 5.45 nm

PROFILE

PV: 86.6 nm
 Tilt Removed

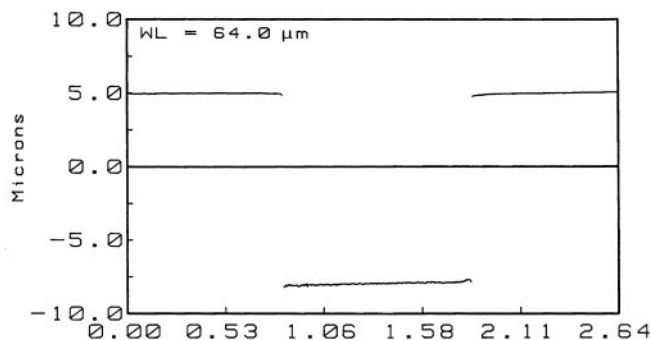


(d) Distance on Surface in mm (5.0X)

13 μm Step
 RMS: 6.30 μm
 RA: 6.13 μm

PROFILE

PV: 13.3 μm
 User Fit

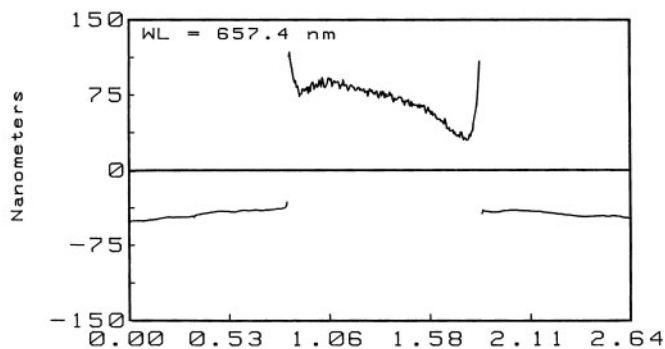


(e) Distance on Surface in mm (5.0X)

13 μm Step
 RMS: 56.6 nm
 RA: 53.8 nm

PROFILE

PV: 180 nm
 User Fit



(f) Distance on Surface in mm (5.0X)

FIGURE 15.28. (Continued)

much less noisy. The repeatability (difference between two consecutive measurements) of the three-wavelength measurement of Figure 15.28(e) is shown in Figure 15.28(f). The RMS of the difference in measurement is 0.67 nm, which yields a dynamic range for the measurement of almost 20,000. Thus, the use of multiple wavelengths can increase the dynamic range of a measurement by a factor of 10. Towers et al. (Towers, Towers and Jones 2003, 2004a, 2004b, 2005) described how to choose an optimal series of multiple wavelengths to create a geometric series of effective wavelengths that yields the greatest increase in dynamic range for each subsequent effective wavelength. The series of four wavelengths in the example given above is an example of an optimal series.

Correction of Single Wavelengths Measurements. In multiple wavelength interferometry like in two wavelength interferometry (Section 7.3), in order to correctly resolve large height discontinuities fringe order (or in other words number of 2π) must also be determined. The longer measurement wavelengths enable larger height discontinuities to be measured, but measurement noise increases proportionately. A longer wavelengths' fringe order can be used to determine fringe order at a shorter wavelength; once fringe order at this shorter wavelength is established, the phase with relatively low noise level can be unwrapped. In this way effective wavelengths created in two and multiple wavelength interferometry are important for extending the range of resolvable heights. A powerful technique for determining fringe order in multiple wavelength interferometry uses a temporal phase unwrapping process (Huntley and Saldner, 1993, 1997; Saldner and Huntley, 1997a, 1997b) rather than the typical spatial process. This temporal phase unwrapping approach works on a series of multiple wavelengths; the values of these multiple wavelengths must form a series of decreasing geometrical wavenumbers.

15.5.3. Reducing Measurement Time

The time required for taking a measurement when using a two or multiple wavelength technique is at least twice as long as when a PSI single wavelength technique is used. In an effort to reduce measurement time, two or multiple wavelength superimposed interferograms can be captured in one frame and then analyzed if the fringes have a carrier frequency (Onodera, 1997). In this case moiré-like interference fringes at the effective wavelength are observed, but if the Fourier transform is applied, then the main frequencies corresponding to interferograms for different wavelengths can be separated and the fractional phases for individual wavelengths can be calculated.

Pförtner and Schwider used a color CCD camera to capture in one snapshot three frames of fringes for wavelengths from three laser sources that corresponded to the RGB colors of the camera (Pförtner and Schwider, 2001). This technique, called RGB interferometry, employed a large wavelength separation (633, 532, 473 nm). In addition, so as to reduce error an axial chromatic dispersion was subtracted without doing any additional measurement. If fringes with carrier frequency were used, only one frame would be needed. However, the carrier approach has its limitations.

Different methods capture simultaneously a few phase shifted interferograms that are spatially separated and captured by one or multiple cameras. Two or multiple sets of interferograms corresponding to two or multiple wavelengths can be registered successively over a period of only 100 μs . A recently introduced separation of interferograms can be done with a specially developed pixilated phase mask that introduces a unique phase shift at each pixel (North-Morris et al., 2004). These methods do not need fringes with a carrier frequency.

Multiple wavelength approaches are also found in other areas of interferometric metrology such as speckle or digital holography. The multiple wavelength approach has also been used in fringe projection methods to increase the dynamic range of their measurements by projecting fringes of multiple frequencies that act like fringes of multiple wavelengths (see Chapter 16).

The applicability of multiple wavelength methods in interference microscopy may be limited by the depth of field of the interference objective that determines measurable heights (see Section 4.1.2) rather than by the effective wavelength. For this reason it is often more practical to use white light interference for which measurable heights are limited by the working distance of the objective.

15.6. WHITE LIGHT INTERFERENCE OPTICAL PROFILERS

White light interference (WLI) optical profilers use broadband illumination and work like an optical focus sensor where the position of the interference signal determines the best focus position. The use of broadband illumination overcomes some of the limitations that are found in single and even multiple wavelength methods. WLI methods have long established themselves as the leading optical profilometers for measuring engineering surfaces like MEMS devices, binary optic, and machined surfaces. The vertical resolution of WLI depends on the analysis of the signal and can be as good as single wavelength PSI methods (0.3 nm), but more commonly is around 3 nm. Vertical resolution here is defined as RMS of the difference measurement on smooth sample.

15.6.1. White Light Interference

A white light source used in an interference optical profiler has a broadband visible spectrum with wavelengths from about 380 up to 750 (violet to red) nanometers. The source has low temporal coherence because of the large wavelength bandwidth, and it is not considered a point source, which means that it also has low spatial coherence. The low temporal and spatial coherence of the source creates interference fringes that are localized in space.

In order to obtain fringes at best focus, the position of the reference mirror needs to be set also at the best focus of the objective. This is done in three steps: first, the reference mirror is moved a few or tens of microns away from focus; second, the objective is focused on the object with some features like the edge of a sharp but not too tall step (fringes are not visible at this moment); and third, the reference mirror is

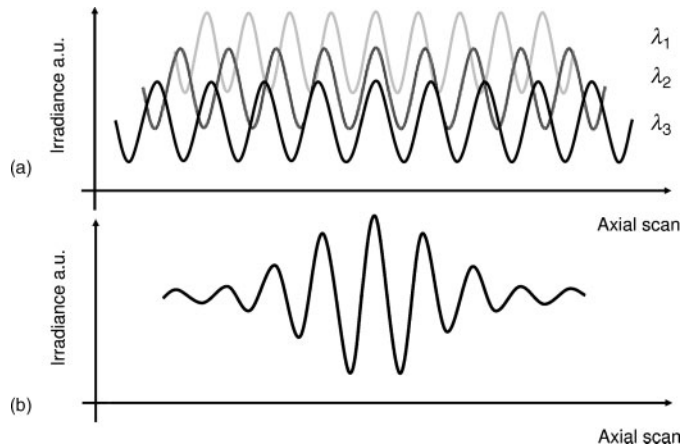


FIGURE 15.29. Formation of white light fringes: (a) fringes for individual wavelengths and (b) sum of fringes of individual wavelengths, which are white light fringes.

brought to focus and stopped when best contrast fringes are obtained. The reference mirror of the interference objective is set at the best focus of the objective in order to obtain the zero OPD.

Because low temporal coherence has a stronger influence on fringe localization than low spatial coherence, temporal effects will be the focus of this discussion. The different wavelengths from the source spectrum are mutually incoherent and the superposition of fringes for individual wavelengths creates white light fringes as shown in Figure 15.29. A monochromatic detector observes the sum of all the fringe intensities. Because the spacing of the fringes for each wavelength of the source is different, the maxima of fringes will align around only one point where the OPD is zero for all wavelengths as shown in Figure 15.29a. Away from this zero OPD position the observed sum of the intensities quickly falls off as shown in Figure 15.29b. It is for this reason that fringes are said to be localized. The fringe with maximum contrast, the fringe that marks the zero OPD, is called the zero order fringe, and each next fringe of smaller amplitude on either side is called $+1$ and -1 , $+2$ and -2 order fringe and so on. The maximum of the zero order fringe does not need to fall at the maximum of the fringe envelope (see Section 15.6.5).

Looking back at Figure 15.26, we see both white light fringes created for a binary grating and quasi-monochromatic fringes for the same object after a narrow band filter is placed in front of the white light source. This pair of interferograms illustrates that when looking at fringes created using a white light source, the zero-order fringe can easily be found across the object, and thus surface shape can be determined without ambiguity. This elimination of ambiguity in numbering fringes (2π ambiguity) is a major strength of WLI because it allows for measurement of samples with large discontinuities and rough surfaces.

In mathematical form this white light interference observed by one pixel during an axial scan can be described as the integral of all the fringes for all wave numbers k

and for different incident angles (for example, de Groot and de Lega, 2004). The resulting fringes in general can be described as

$$I(z) = I'[1 + \gamma(z) \cos(k_0 z)] \quad (15.19)$$

where I' is the background intensity, $\gamma(z)$ is the fringe visibility function or coherence envelope and $k_0 = 2\pi/\lambda_0$ is the central wave number for fringes under the envelope. $\gamma(z)$ is proportional to the modulus of the Fourier transform of the source spectrum. Generally, if the light source has a Gaussian spectrum, then the envelope of the fringes can be described also as a Gaussian function $\gamma(z)$. The broader the bandwidth of the source spectrum, the narrower the width of the envelope. The width of the fringe envelope determines the coherence length of the source (see Sections 15.4.1.2 and 15.4.1.3); for a white light source this width is of the order of 1–2 μm . The envelope of the fringes varies with other factors like sensitivity of the camera, the measured object, and dispersion in the system also.

15.6.2. Image Buildup

The important feature of white light fringes for surface topography measurement is the fact that fringes are localized and can only be found within microns or tens of microns of the zero OPD as shown in Figure 15.30. As the objective (or the sample) is scanned axially through focus, each pixel registers irradiance; the highest point on the fringe envelope determines the best focus position on the sample. Figure 15.31 shows a few interferograms as registered by CCD camera as a sample is progressively scanned through focus. Fringes at individual interferograms show which part of the sample is in focus for a given position of the scan.

15.6.3. Signal Processing of White Light Interferograms

The shape of the object is determined from the localization of the fringes at each spatial point registered during the axial scan. It is assumed that the fringe signal is the

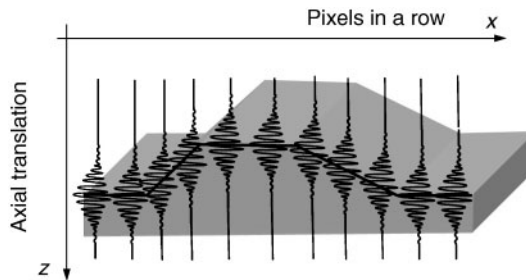


FIGURE 15.30. Irradiance signals as observed by a few pixels in a row for an object placed in white light interferometer.

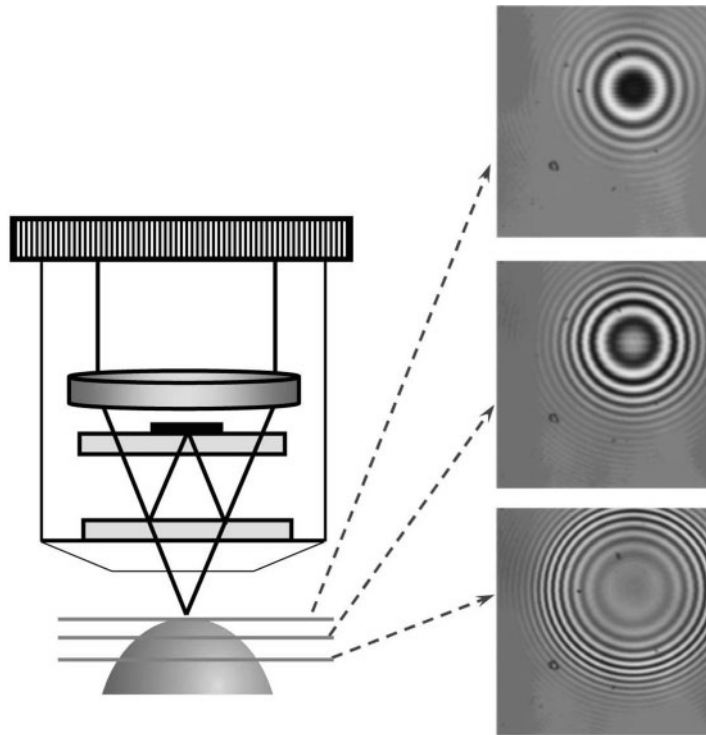


FIGURE 15.31. White light interferograms for a spherical object as obtained for a few positions of the objective during an axial scan.

same at each point and only its axial position is different due to changes in the topography of the test sample. Since 1980 (Balsubramanian, 1982), a number of methods and algorithms have been developed that describe the use of white light interferometry. Many algorithms first compute the envelope (modulation) of the fringes. The fringe envelope can be calculated in the same way as the modulation of fringes is determined in PSI. During the axial scan, the OPD is changed typically by 90° between registered frames but over a much longer scan range than with PSI. Then, any PSI algorithm can be implemented to determine the modulation of the fringes at each point along the axial scan.

For a common 5-frame PSI algorithm (Schwider et al., 1983; Hariharan et al., 1987) the modulation would be calculated as

$$\gamma(z) = \frac{\sqrt{(I_2 - I_4)^2 + (I_1 - 2I_3 + I_5)^2}}{\text{normalization}} = \frac{\sqrt{N^2 + D^2}}{\text{normalization}} \quad (15.20)$$

where the N and D represent numerator and denominator of any PSI algorithm. Properties of PSI algorithms that can be used for modulation calculation were nicely

reviewed by Larkin (1996b). Kino and Chim (1990) proposed using the Fourier transform technique to calculate the envelope where the forward Fourier transform of the interference signal is computed. After these calculations three lobes are observed. One sidelobe, which is positioned at the frequency of the fringes, is isolated and shifted to the center. The width of the sidelobe is inversely proportional to the bandwidth of the source. Caber (1993) proposed using electronic hardware (amplitude demodulation in hardware) to obtain the envelope of fringes.

Once the envelope is determined, its position can be found by fitting the curve to the envelope and finding its position. The position of the envelope can be also found by calculating the envelope's center of mass using the equation:

$$h = \frac{\sum_{i=1}^{N-1} \gamma_{zi} z_i}{\sum_{i=1}^{N-1} \gamma_{zi}} \quad (15.21)$$

where γ represents the envelope function, z the axial position, and h the object's height. The center of mass algorithm is very fast and computationally efficient, and often is implemented in confocal systems for finding the maximum of the confocal irradiance signal. Center of mass calculations are equivalent to calculations of the maximum of the envelope position but only for a symmetrical signal. For an asymmetrical signal, a piston is introduced for each point; however, this piston does not affect the whole measurement. The most precise measurement of the fringe envelope is done using an achromatic phase shifter. At each axial scan position, an achromatic phase shifter, which is described in Section 15.8.9, shifts the fringes underneath the envelope, which results in the registered constant modulation of the fringes. Instead of finding the position of the envelope, it is also possible to find the position of the bright or dark fringe around the envelope's maximum (Park and Kim, 2000).

De Groot and Deck (1995) showed that finding the position of the fringe envelope can be done by processing it in the frequency domain. First, the Fourier transform is calculated (similar to Kino and Chim) and one sidelobe is isolated. The magnitude of the sidelobe represents the strength of the spectrum at a given wavelength, and the phase represents the phase of the interference signal for a given wavelength. Thus, from this sidelobe, each interference component of the white light signal can be recreated $I(k) = I(k) \times \cos(\varphi(k))$, where $\varphi = kz$. If the phase for at least two wavelengths is known, z can be determined without 2π ambiguity from $z = \Delta\varphi/\Delta k$. Other methods like wavelets analysis also can be implemented (Yatagai, 1994; Itho et al., 1995; Sandoz, 1997; Recknagel and Notni, 1998); the upside of this method is reduction in noise but the downside is longer processing time.

At first, white light interference microscopes were used for testing of smooth surfaces (Davidson et al., 1987; Kino and Chim, 1990; Lee and Strand, 1990) and then extended to measurement of rough surfaces (Häusler and Neumann, 1992) in which the presence of speckles may need to be considered (Häusler and Herrmann,

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1992; Pavlíček and Soubusta, 2003). The signal can be analyzed to obtain not only the shape of the object but also to map of an object's different reflectivities or an object image as seen by the objective with infinite depth of focus can be displayed (Sheppard and Roy, 2003). This is not a complete list of the literature describing algorithms for WLI.

Sampling of White Light Interference Signal. Measurement time in WLI varies with the required scan length; thus, the sampling rate of WL fringes has to be carefully considered so as to obtain the best data within the shortest time frame. In order to localize fringes, the value of the envelope's amplitude needs to be known at only a few axial points (Creath, 1997; Larkin, 1996a, 1996b) and not all fringes need to be resolved during the scan. For example, calculating the fringe modulation with PSI algorithms, which was described in Section 15.4.1.3, requires four samples per fringe; however, if sampling is done not at four samples per fringe but rather at four samples per odd number of fringes, faster but less precise WLI measurements can be obtained. Sampling with four samples per odd number of fringes is equivalent to sampling at every 90° ; not all fringes will be resolved, but calculating the fringe modulation is still possible. Using this method, measurement speeds can be increased 23 times (Schmit, 2003) up to $100 \mu\text{m s}^{-1}$ using a 60 frames per second camera frame rate. The sampling rate would then equal about $1.8\text{--}2 \mu\text{m}$ and is on the order of the coherence length of the white light source. When the sampling rate approaches the coherence length of the source, data become unusable. When this occurs, the envelope of the fringes needs to be lengthened by reducing the spectral bandwidth of the source. Sampling issues in different WLI algorithms were discussed by a number of authors (Deck and de Groot, 1994; Larkin, 1996a, 1996b; Creath, 1997; Hirabayashi et al., 2002; Schmit, 2003). Fringe projection used in a stereoscopic microscope creates localized fringes that are analogous to fringes in white light interferometry but of longer wavelength and envelope; thus, the sampling rate can be larger than a few microns (Kröner et al., 2001; Kröner et al., 2006).

Increased Resolution White Light Interferometry. PSI methods achieve about 10 times better vertical resolution (0.3 nm vs. 3 nm) than WLI methods when measuring the position of the fringe envelope; however, if the phase of the fringes under the envelope is found, WLI methods can achieve similar vertical resolution. This high resolution WLI method combines a lower resolution map of the envelope position and a higher resolution map of the phase (position) of the zero-order fringe. The calculation of these two maps and the combination of them can be accomplished using various algorithms (Cohen et al., 1992; Larkin, 1996b; Windecker et al., 1999; Harasaki et al., 2000; de Groot et al., 2002). This high resolution WLI is particularly well suited for determining the shape of smooth surfaces with large height differences such as binary diffractive optics or micro-electromechanical systems (MEMS). The advantage of this method is that the phase is calculated always at the best focus position. Examples of measurements with white light interference optical profilometer are given in Figure 15.32.

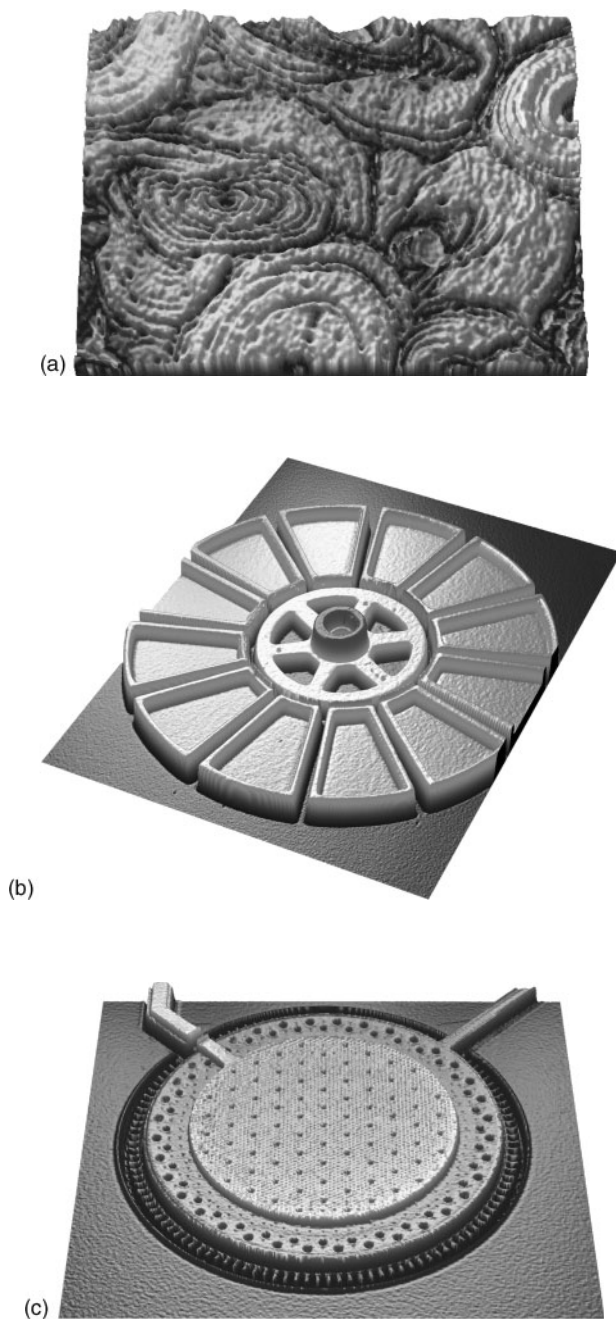


FIGURE 15.32. Examples of object measurement with white light interferometer (a) Forensic bone sample, $460\ \mu\text{m} \times 612\ \mu\text{m}$, (b) salient type micro-motor, $230\ \mu\text{m} \times 304\ \mu\text{m}$ (c) solderless MEMS microphone for cellular phones and other applications, $0.9\ \text{mm} \times 1.2\ \text{mm}$ (d) honed cylinder wall, $1.2\ \text{mm} \times 0.90\ \text{mm}$. Courtesy Veeco Instruments.

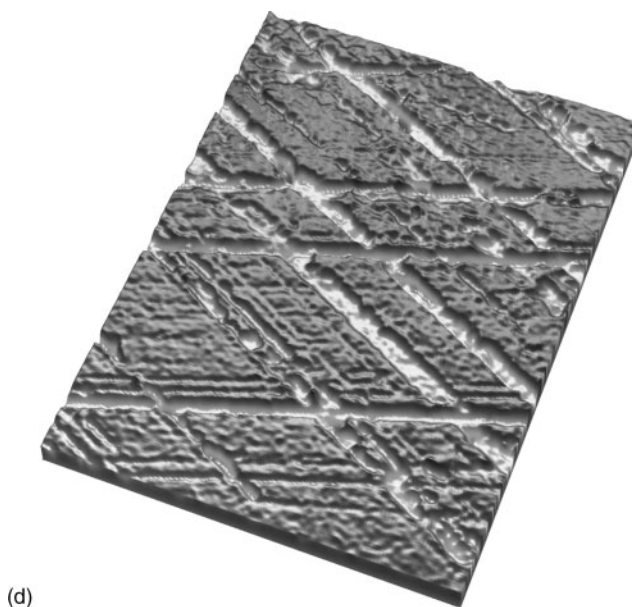


FIGURE 15.32. (Continued)

15.6.4. Light Sources

Different white light sources, such as a tungsten–halogen, incandescent or arc lamp, LEDs and SLDs can be used for illumination. These sources have different spectra and thus create different fringe envelopes. The width of the fringe envelope is determined by the bandwidth of the source spectra. In Figure 15.33, we see that the two sources, a halogen lamp and a red LED, their spectra having different bandwidths, generate fringes with different envelope widths. The narrower the envelope, the more precisely the localization of fringes can be determined. The spectra of semiconductor light sources, such as light emitting diodes (LEDs) and superluminescing laser diodes (SLDs), are similar in shape to a Gaussian function.

15.6.5. Dispersion in White Light Fringes

In Figure 15.29, it was assumed that a white light interferometer is compensated for all wavelengths, meaning that the position of the maximum of the fringes aligns with the maximum of the envelope, namely where there is a zero phase shift $\varphi_0 = 0$ between fringe and envelope maxima. If there is an odd number of reflections from dielectric surfaces in one arm of the interferometer and an even number in the other, the fringes will be shifted by $\varphi_0 = 180^\circ$ under the coherence envelope, and the minimum of the fringe will align with the maximum of the coherence envelope.

In a real system the fringes may be shifted with respect to the envelope by any amount of φ_0 , and this shift may be due to any number of factors. These factors

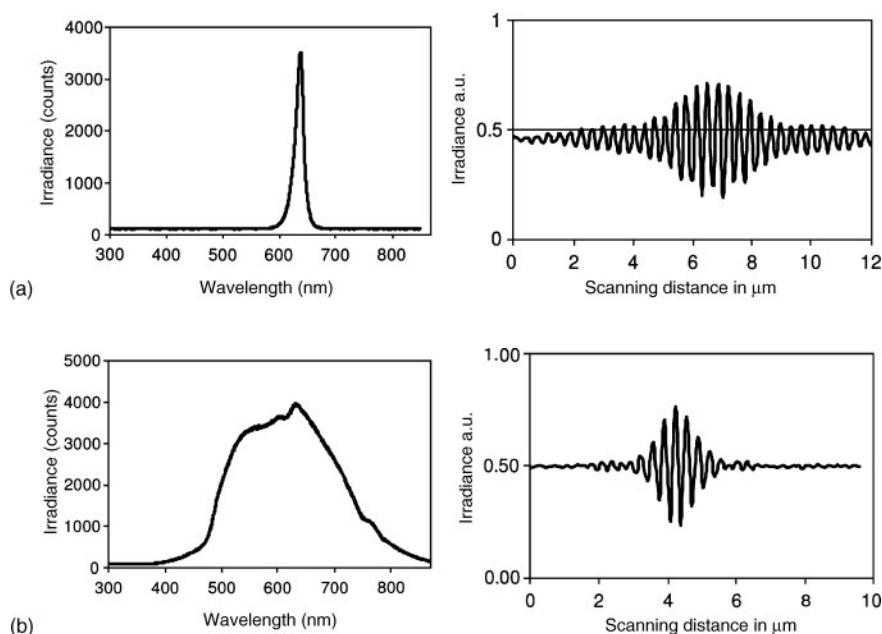


FIGURE 15.33. Spectrum and interferogram for (a) halogen lamp and for (b) red LED source.

include reflection from non-dielectric surfaces and transparent films, dispersion and lateral aberrations of the system or the presence of a transparent plate in one of the arms of the interferometer. These factors cause a phase shift that varies with the wave number, which is also called the spectral phase. The spectral phase introduces changes into the white light interferogram; it changes the envelope and position of the fringes and the fringe frequency. If the introduced spectral phase is linear with the wave number, the fringe location changes but the shape of the envelope of fringes remains the same. The constant phase change on reflection for all wave numbers only shifts the fringes underneath the coherence envelope, like an achromatic phase shifter would (see Section 15.9.2.). Higher order changes in the spectral phase will influence the position, shape, and amplitude of the envelope as well as the fringe frequency.

Dissimilar Materials. As long as the object's surface is comprised of a single material, the spectral phase does not present a problem since only a constant offset is introduced. However, when two dissimilar materials are side-by-side on the surface, they will have different phase shifts upon reflection for different wavelengths (unless both of them are dielectric materials with the imaginary part of the index of refraction $k = 0$) and the measured height difference at the boundary where the two meet will be incorrect. By knowing the optical constants of the different materials for the wavelengths used in the measurement, it is possible to correct for this difference (Bennett, 1964; Church and Lange, 1986; Biegen and Smythe, 1988; Doi et al., 1997; Rogala and Barrett, 1998; Harasaki et al., 2001; Park and Kim,

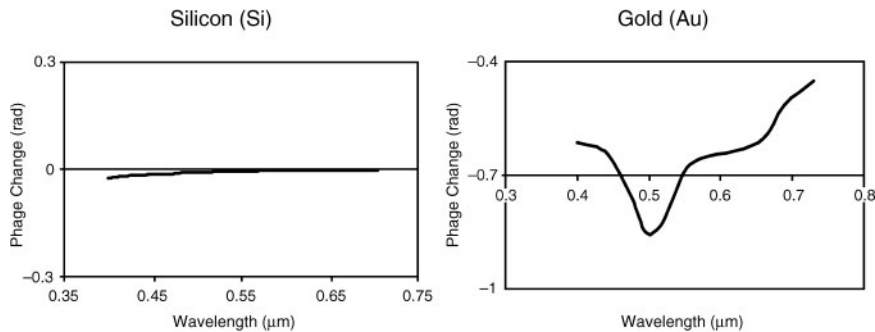


FIGURE 15.34. Phase change on reflection for different wavelengths: (a) silicon and (b) gold.

2001). The phase change on reflection for bulk materials for normal incidence for a given wave number k is described as

$$\varphi_{\text{material}}(k) = \tan^{-1}\left(\frac{2k}{1 - n^2 - k^2}\right) \tag{15.22}$$

where n and k are the real and imaginary index of refractions, and the values of n and k for the indices of refraction for the range of wavelengths of the materials used in the test object can be found in *The Handbook of Optical Constants of Solids* by Palik (1991). Often a better solution when faced with a test object made of a composite material, such as ceramic, is to coat the material with a layer (typically 100 nm is sufficient) of opaque material (i.e., a metal) so as to obtain a good profile of the surface. Alternately, replicas of the test object can be made and then measured.

When a wide spectrum source is used, the phase change on reflection over the entire spectrum needs to be considered. Figure 15.34 shows spectral phases for gold and silicon as examples of metal and semiconductor materials. In white light interferometry the spectral phase introduced by the different materials of the object will shift the peak of the envelope (most of metals) and possibly even change the shape of the envelope (gold and possibly some semiconductors). For typical materials this shift will not be larger than 40 nanometers (Harasaki et al., 2001). Table 15.3

TABLE 15.3. Offset in measured heights due to shift of envelope peak position and monochromatic fringes at 600 nm wavelength due to phase change on reflection for different metals.

Metal	Height offset due to envelope peak shift (nm)	Height offset due to fringes shift (nm)
Silver	36	25.1
Aluminum	13	12.7
Gold	0	33.4
Molybdenum	59	13.4
Nickel	15	20.8
Platinum	13	18.1

shows the shift in the peak of the envelope for white light fringes and the phase of the fringes for 600 nm wavelength.

Thick Film Measurement. If the sample is covered with a transparent film that is more than a few microns thick, two sets of localized fringes separated from each other are generated, one for each interface. A thick film technique is then used to measure the film thickness. For the second interface, the bottom of the film, a phase shift between interference patterns for individual wavelengths proportional to the product of the geometrical path and the index of refraction equal to $d \times n(k)$ is introduced, and the irradiance for the white light fringes for the second interface can be described as

$$I(z) = \int_{k_1}^{k_2} \langle 1 + V(z) \cos\{kz - kd[n(k)]\} \rangle dk \quad (15.23)$$

The dependence of the refractive index on the wave number k can be described to first approximation as a linear expansion:

$$n(k) = n(k_0) + \frac{dn}{dk}(k - k_0) \quad (15.24)$$

The linear dispersion shifts the envelope by the group index of refraction times the thickness of the dispersive element; this dispersion also shifts the fringes under the envelope slightly.

A simple technique for finding the relative position of the peaks of the fringe envelopes can be implemented to find the thickness of a film. Figure 15.35 shows two almost clearly separated sets of fringes formed for the air/film and film/substrate interfaces. The typical range of measurable film thicknesses runs from 3 to 150 μm depending on the dispersion of the film and NA of the objective.

Higher order dispersion introduced by a thicker film or an inserted plate may have many effects; the envelope may widen or even become asymmetrical, the position of

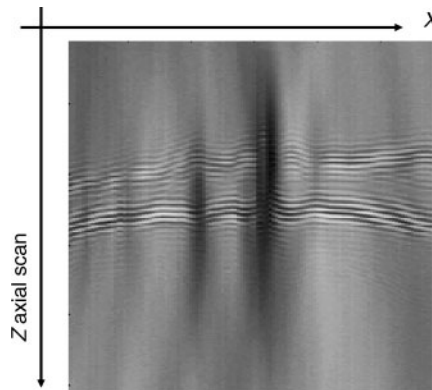


FIGURE 15.35. White light fringes as observed by a row of pixels during axial scan for (a) nonconformal film, where the top fringes are created at the air/film interface while the bottom fringes correspond to film/substrate interface but are located below the interface.

the fringes may shift under the envelope, fringes may lose contrast, or the period of the fringes may change with the z position (Pavlíček and Soubusta, 2004). Dispersion effects will be stronger for sources with a wider spectrum and objectives with a higher NA. However, the observed changes will be different for different shapes of the spectra. Thus, to measure thicker films, it is better to use a low numerical aperture objectives and a narrower bandpass of the white light source.

Thin Film Measurement. When the optical thickness of the film is shorter than the coherence length of the white light source, typically less than $3\text{ }\mu\text{m}$, multiple reflections introduce an additional nonlinear term in the spectral phase that causes changes in the fringe envelope and the frequency of fringes (Hariharan and Roy, 1996; Roy et al., 2005). Finding the envelope peak position is not valid any longer since the localized fringes at both interfaces are not separated. A different approach has to be taken. One approach is to apply the Fourier transform of the measured signal and calculate the spectral phase under the first lobe in the frequency domain (Kim and Kim, 1999). Figure 15.36 shows fringes for thin film (a), the magnitude of first spectral lobe (b), and the corresponding spectral phase in the frequency domain (c). In general, when using interferometry to measure thin or thick films, not only their thickness, but the top and bottom profiles are also measured. The spectral phase for the thin film interference has the form of a polynomial; thus, the polynomial for the chosen film model (n and k) is fitted, and regression analysis is used to find the best fit and, therefore, the film thickness. The spectral phase due to the dispersion of the system needs to be known and subtracted for better accuracy. Instead of calculating the spectral phase and finding best fitting simulated spectral phase, the magnitude can be

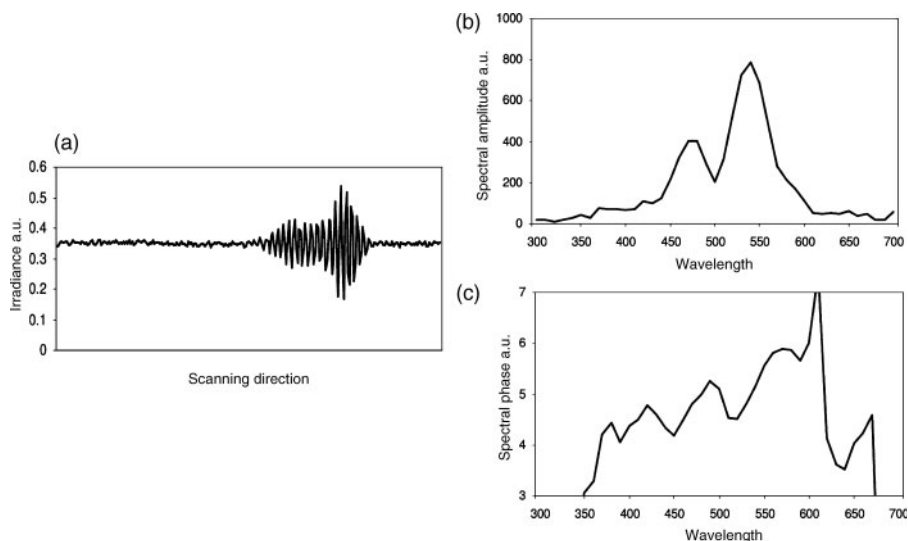


FIGURE 15.36. (a) White light fringes for thin film, (b) the side lobe of the Fourier transform magnitude, and (c) spectral phase under the side lobe.

calculated, and the best fitting simulated magnitude can be found to determine film thickness. These methods are used for films of thickness from a few microns down to 100 nanometers. For films of optical thickness less than 100 nm, the sensitivity of the method drastically decreases.

Besides special analysis necessary for measuring objects with dissimilar materials and films, objects with narrow trenches (10 μm wide and less) also require careful examination of the fringes. For a narrow structure, additional unwanted fringes are created that do not correspond directly to the object shape (Montgomery et al., 2004; Schmit, 2003; Tavrov et al., 2005)

Measurement through the Glass Plate or Liquid Media. Many engineering objects, like MEMS devices, are often protected by a cover glass, and some devices in environmental chambers need to be tested under different pressures or temperatures. Such objects require testing through a cover glass. Biological samples are often immersed in liquid and require measurement through this liquid. Because of the dispersion of the liquid layer or cover glass white light fringes may be totally washed out. Thus, a compensating plate needs to be introduced in the reference arm of interferometer. This compensation is the most easily done for Michelson-type objectives. In addition, the contrast of fringes diminishes faster for higher numerical aperture objectives, which are used as both illuminating and imaging optics. It is also difficult to introduce compensation for higher NA objectives. In order to increase fringe contrast for systems with high numerical aperture objectives, the numerical aperture of the illumination can be reduced by delivering a nearly collimated illuminating beam (Han 2006) of very low numerical aperture directly to the interferometer underneath the objective and not through the objective as shown in Figure 15.37(a). Figure 15.37(b) shows a measurement of grating immersed in liquid and a pitch standard as measured through 3 mm cover glass with 20X objective.

15.6.6. Other Names for Interferometric Optical Profilers

White light interferometry with an axial scan for the measurement of engineering surfaces has been variously labeled and can also be found under the following names:

- White light interferometry (WLI)
- Vertical scanning interferometry (VSI)
- Low coherence interferometry (LCI)
- Coherence probe
- Optical coherence profilometry (OCP)
- Optical coherence microscopy
- Scanning white light interferometer (SWLI)
- White light scanning interferometry (WLSI)
- Coherence probe microscopy (CPM)
- Correlation microscopy
- Phase correlation microscopy
- Interference microscope
- Microscopic interferometry
- Wide band interferometry

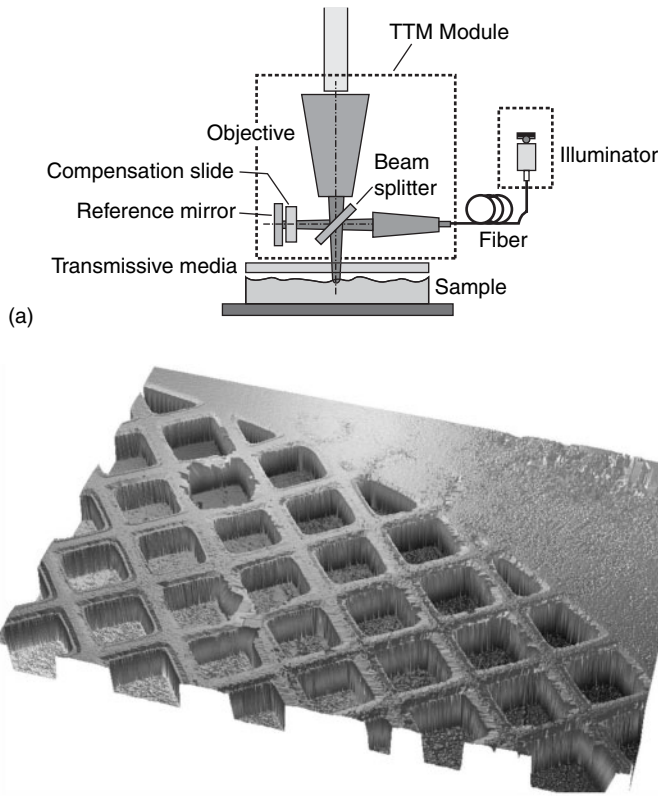


FIGURE 15.37. (a) Michelson type interferometric objective for observation of sample through cover glass with illumination provided not through the objective but from the side of the interferometer with a beam of a very low numerical aperture used to increase the contrast of the fringes, (b) cross hatch grating immersed in water measured with through the media objective with compensating cell/plate in the reference arm. Scan area $620 \times 460 \mu\text{m}$. Grating height: $30 \mu\text{m}$. Courtesy Reed and Gimzewski from UCLA.

Full field OCT

Wide field OCT

Coherence radar

Fringe peak scanning interferometry

The equivalent method for biological samples is called mainly optical coherence tomography (OCT), but can also be called time domain OCT (TD-OCT), coherence radar or confocal interference microscope.

15.7. WAVELENGTH SCANNING INTERFEROMETER

An alternative to white light and multiple wavelength interferometers is the spectral interferometer, which takes advantage of spectral interference fringes for a wide range of wavelengths. These spectral fringes can be obtained through the scanning of the source wavelength or dispersing white light fringes with a spectrometer.

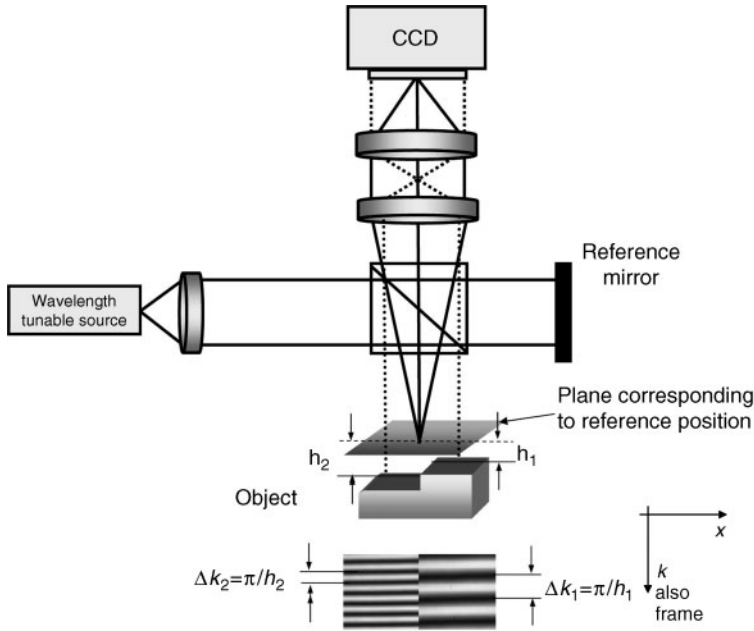


FIGURE 15.38. Schematic of spectral interferometer with wavelength scanning.

Spectral interferometry with wavelength scanning uses a setup that is typically based on a Michelson interferometer with the difference being a light source that is wavelength tunable (see Fig. 15.38). This system does not require point by point axial mechanical scanning as in typical confocal microscopy, or field axial scanning as in white light interferometry in order to find the best focal position for each point. Instead, fringes of different frequencies are observed by sweeping the light source through wavelengths from which the height of the object with respect to the reference mirror is determined. This wavelength scanning profiler delivers topographies of smooth and rough surfaces with no 2π -phase ambiguity problem. One advantage that a wavelength scanning system has over a white light setup is that the contrast of the fringes remains good even for dispersive media.

15.7.1. Wavelength Tunable Light Sources

Because the tuning range of the wavelength determines the resolution of the measurement and the tuning step of the wavelength determines the system's measurable depth (see Section 15.7.2), illuminating systems are continuously being developed to increase the scanning range and decrease the scanning resolution. At first, large expensive dye lasers, which were inconvenient for industrial purposes, and Ti:Sapphire lasers (Kuwamura and Yamaguchi, 1997; Yamamoto et al., 2001) were used. At the same time, new and much more convenient tunable solid state lasers were also being

used. A standard method of varying the wavelength in a diode laser is to change the injection current or chip temperature; however, these methods are subject to mode hops and changing of mode shape. To avoid these mode-hops, Tiziani et.al. (1997) used an external resonator like those used in dye lasers. Later, broadband sources like a superluminescent diode in combination with wavelength-tuning devices like an acousto-optical tunable filter or a liquid crystal Fabry–Perot interferometer (Mehta et al., 2002) were proposed as more convenient and stable illuminating systems.

15.7.2. Image Build-Up

The interference signal at each x, y point can be described using Eq. (15.8), which is now

$$I(k, h) = I_R(k) + I_0(k) + [2I_R(k)I_0(k)]^{1/2} \cos(2kh) \quad (15.25)$$

where h is the path difference between corresponding points on the reference. Since the object is not moving, it is assumed that $z = 0$. The variation in h across the field determines height variations of the object. As mentioned in Section 15.6.1 this path difference $2kh$ can be changed in a few different ways. With mechanical axial scanning of the object by δh (previously marked as z) distance at a time (like in scanning white light or phase shifting interferometry), the optical path difference for a given wave number k , for each point on the object, would change by the same amount $\delta\varphi = 2k\delta h$ creating fringes of the same frequency for each point as shown in Eq. (15.26) and Figure 15.39.

$$I(k, h) = I_R(k) + I_0(k) + 2[I_R(k)I_0(k)]^{1/2} \cos(2k(h + \delta h)) \quad (15.26)$$

In wavelength scanning interferometry the optical path length change for each point on the object is caused by the wavelength change expressed as δk , and the change in the optical path difference is expressed as $\delta\varphi = 2\delta kh$. The irradiance during the wavelength scan for each point can be expressed as in Eq. (15.27)

$$I(k, h) = I_R(k) + I_0(k) + 2[I_R(k)I_0(k)]^{1/2} \cos(2h(k + \delta k)) \quad (15.27)$$

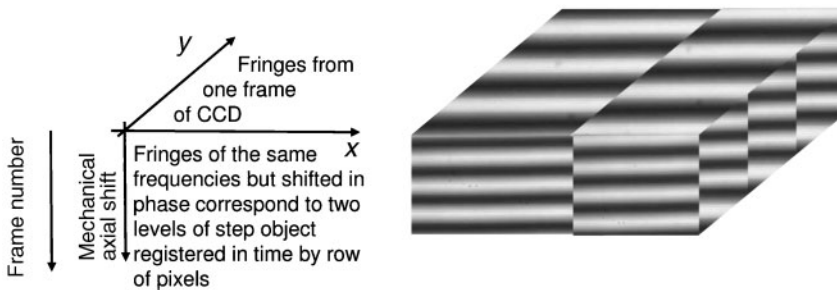


FIGURE 15.39. Fringes in monochromatic illumination for the step object as obtained with PZT scanning.

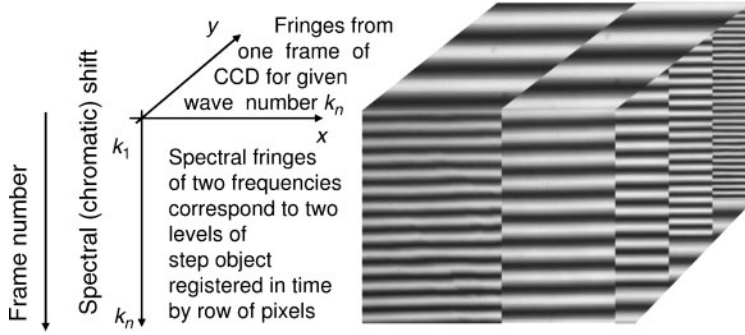


FIGURE 15.40. Fringes for the step object as obtained with wavelength scanning.

and is called spectral interference. The variation in the optical path difference due to the shape of the object creates fringes of different frequencies for points across the object during the wavelength scan. Figures 15.39 and 15.40 show fringes as obtained for a step object that is tilted around the x axis with the optical path length introduced by axial mechanical scanning and wavelength scanning, respectively. For a mechanical scan that uses monochromatic illumination, fringes of the same frequency but with a different initial phase for different step levels are created; for wavelength scanning two distinct frequencies for two step levels are created. Small variations in object shape result in small changes in the fringe frequency across the object.

The path change at each point as a function of wavelength change equals

$$\delta\varphi = 2\delta kh = 4\pi h \frac{\delta\lambda}{\lambda^2} \quad (15.28)$$

The period of the fringes at each point can be expressed in terms of wavelength shift Δk for which the optical path change $\Delta\varphi$ is equal to 2π

$$\Delta\varphi = 2\Delta kh = 2\pi \quad (15.29)$$

From the frequency of the detected fringes, at each point the height of the object h can be determined by Eq. (15.30)

$$h = \pi/\Delta k = \Delta\varphi/2\Delta k. \quad (15.30)$$

Finding the height from the fringe frequency is equivalent to finding the height from the rate of the optical path change at each point, called phase slope or spectral phase.

The scanning wavelength range can be from a few nanometers to tens of nanometers and the tuning step of the wavelength is typically on the order of a fraction of nanometers (see Fig. 15.41). With this technique submicron resolution is

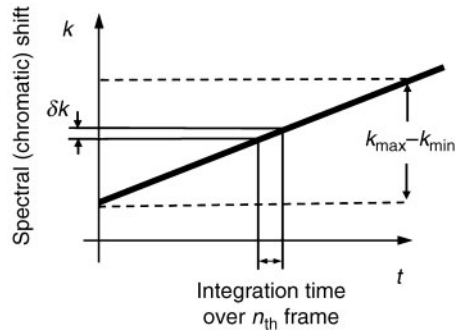


FIGURE 15.41. Wavelength tuning in wavelength scanning interferometer.

possible with a height range of a few millimeters. The maximum measurable height is determined by the wavelength's tuning steps as

$$\Delta h_{max} = \pi / \delta k \frac{\lambda^2}{2\delta\lambda} \quad (15.31)$$

and the minimum measurable height difference is determined by the total tuning range as

$$\Delta h_{min} = \pi / (k_{max} - k_{min}) \quad (15.32)$$

However, other factors influence these values; for example, the depth of field of the objective may limit the maximum measurable depth of the object (see Section 15.4.1.2.).

15.7.3. Signal Analysis

As explained in the previous section, information about the relative distance between the object and reference plane can be retrieved by finding the fringe frequency or optical path change rate at a given point. At first, the fringe frequency was determined by counting the number of zero-crossings of the signal at each pixel. Later, a method based on the Fourier transform calculation was developed (Takeda and Yamamoto, 1994; Barnes et al., 1996; Yamaguchi et al., 1998). Figure 15.42 shows three interferograms for three different objects at one wavelength during a wavelength scan. Also shown is the signal as recorded by a pixel during a wavelength scan and the Fourier transform of the signal with the peak position determining the height of the object. To further improve the resolution of the Fourier transform technique, the rate of optical path change (spectral phase slope) along the spectral interference can be calculated (Kinoshita et al., 1999; Mehta et al., 2003a; Mehta et al., 2003b). Wavelength scanning interferometry requires tens or hundreds of registered interferograms during the wavelength scanning of the source. The measurement time in wavelength scanning interferometry is the same for shallow and deep surfaces because the number of required frames does not depend on sample's depth like in white light interferometry.

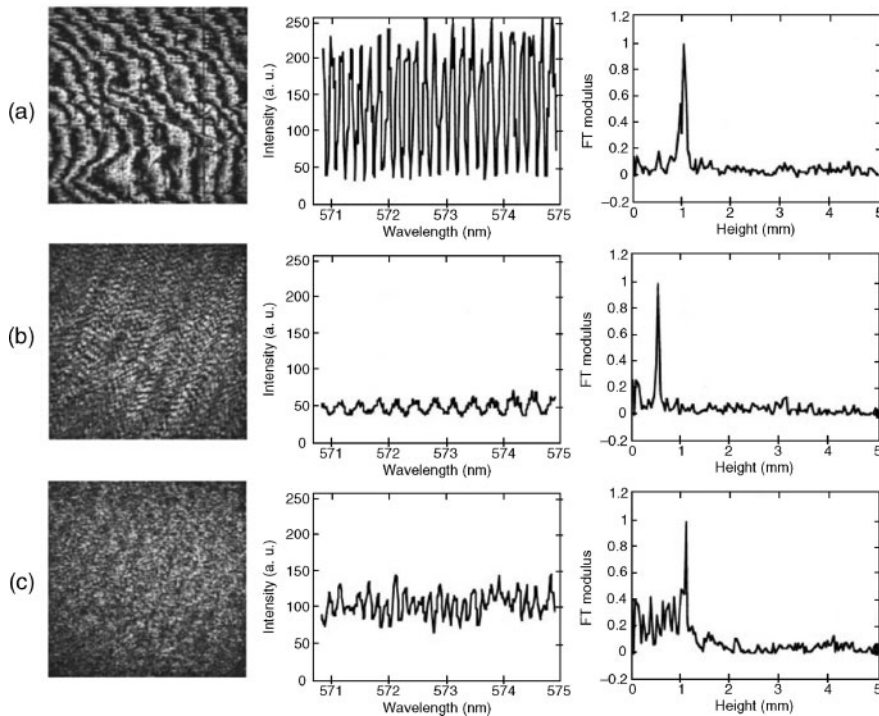


FIGURE 15.42. Interference patterns at a single wavelength, interference signals (spectral fringes) as seen by a single pixel during the wavelength scan in time, and the Fourier transform of the interference signal for (a) polished steel, (b) milled duralumin, and (c) a MgO coated surface. Reprinted with permission from Yamaguchi et al., 2000.

In the Michelson interferometer object height can be, in relative terms, on both sides of the reference mirror. Because the methods described here solve only for the magnitude of the object's distance from the reference, not its direction, a height ambiguity problem exists. Figure 15.43 shows the height ambiguity that can be created. In these cases, a special phase unwrapping procedure must be applied (Paulson et al., 2000), or a phase unwrapping procedure known as temporal phase unwrapping (Huntley and Saldner, 1993, 1997; Saldner and Huntley, 1997a, 1997b, Huntley and Coggrave, 1998) must be applied to wavelength scanning interferometry. If the object were shifted above or below the focus plane, no unwrapping procedure would be necessary because the object would be clearly on one side of focus or the other. Shifting the object away from focus increases the frequency of fringes at each point as shown in Figure 15.44. However, this shifting could limit the maximum measurable height range because the object may be shifted out of the focus range or the fringe frequency may become too dense to be resolved (see Eq. (15.31)). The resolution of the measured height, in addition to the wavelength scanning range, also depends on the roughness of the tested object and the distance from the point of best focus (Yamaguchi et al., 1998).

In a Fizeau setup multiple reflections between the reference and the object must be accounted for in the signal analysis (Yamaguchi et al., 2000), and although the

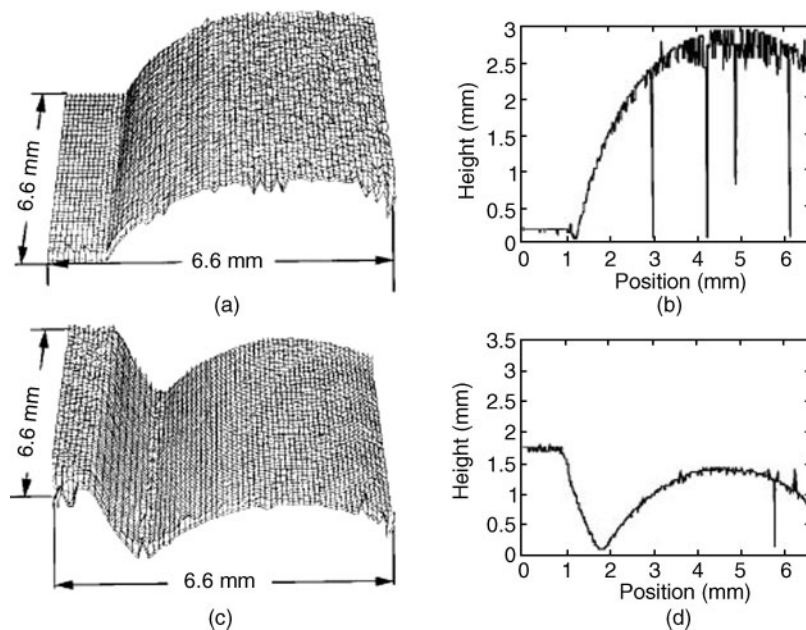


FIGURE 15.43. Wavelength scanning interferometry results for cylindrical surface positioned away from the virtual focus position of the reference mirror (a) surface, (b) plot and results showing possible sign ambiguity problem if the object surface crosses virtual focus position of the reference surface, (c) surface, and (d) plot. Reprinted with permission from Yamaguchi et al., 2000.

resultant signal is not sinusoidal as in a Michelson setup, the fundamental period of the signal is the same. In the Fizeau setup the object is on one side of the reference mirror and no ambiguity in height derivation exists.

Wavelength scanning is used in a number of optical methods such as optical frequency domain reflectometry, distance measurement (Kikuta et al., 1986), speckle interferometry and, recently, digital holography (Kim and Kim, 1999; Pawlowski

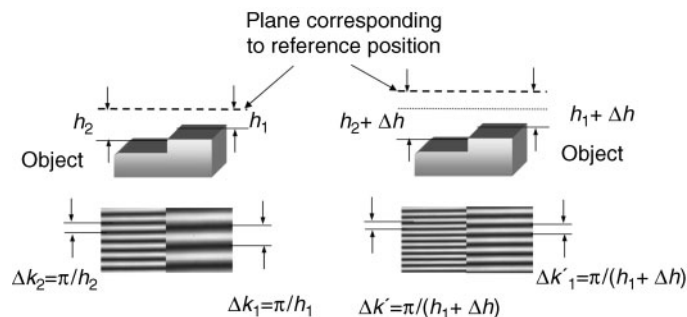


FIGURE 15.44. Fringes in wavelength scanning interferometer for two different positions of the object along the optical axis. Increase in distance between reference mirror and object results in increased fringe frequency.

et al., 2004). An overview of wavelength scanning interferometry and its applications was done by Tiziani (2000) and Takeda et al. (2005).

15.7.4. Film and Plate Thickness Measurement

A wavelength scanning interferometer can be used not only for shape measurement but also for thickness measurement (or its dispersion) of a transparent object. In this case due to reflections of the wavefront of multiple optical interfaces many interferograms are created and superimposed. Each interfering pair of reflected wavefronts of almost plane and parallel wavefronts creates spectral fringes of the main frequency characteristic for the average optical path difference during the wavelength scan. Some of these reflections are unwanted, and over the last 15 years methods based on separating these different interferograms in the data processing stage have been developed so as to avoid immersing the sample in oil or coating the surfaces with an index-matching lacquer (Okada et al., 1990; Deck, 2003; de Groot, 2000; Burke et al., 2006; Hibino et al., 2003; Hibino et al., 2004; Hibino and Takatsuji, 2002). However, these techniques could not be applied to measure thicknesses down to a few microns. Measurement of transparent layers of a few microns in thickness is often laid on optoelectronic devices, and at these small thicknesses separating the different frequencies was impossible until Kim (Kim et al., 2002; Kim and Kim, 2004) proposed a technique, similar to the one applied to WLI, to measure these tiny thicknesses.

15.8. SPECTRALLY RESOLVED WHITE LIGHT INTERFEROMETRY (SRWLI)

Spectral interference fringes for a wide range of wavelengths can be also observed by dispersing white light fringes with a spectrometer. This method of observation of spectrally resolved fringes is called spectrally resolved white light interferometry and is an alternative to wavelength scanning that was described in the previous section. The main advantage of SRWLI is that profiles with discontinuities up to tens of microns can be calculated from a single spectral interferogram.

Although the first spectrally resolved white light interferometer for surface profilometry described by Schwider and Zhou (Schwider and Zhou, 1994) was based on the Fizeau interferometer, these systems are typically based on a Michelson system. In order to observe spectrally resolved fringes, these interferometers use a spectrometer in conjunction with the CCD camera. The plane of fringe localization is imaged through the entrance slit of spectrometer onto the CCD camera as shown in Figure 15.45. The spectrometer splits the single line of the object's white light fringes into spectral fringes along the chromatic axis of the CCD camera. Different types of spectrometers can be used, such as a prism or grating spectrometer.

The observed fringes are basically the "channeled spectrum" that scientists observed about 100 years ago. In this respect spectrally resolved interferometry is not a new technique; however, the development of computers and solid state devices and spectrometers has allowed for the utilization of the channel spectrum for many

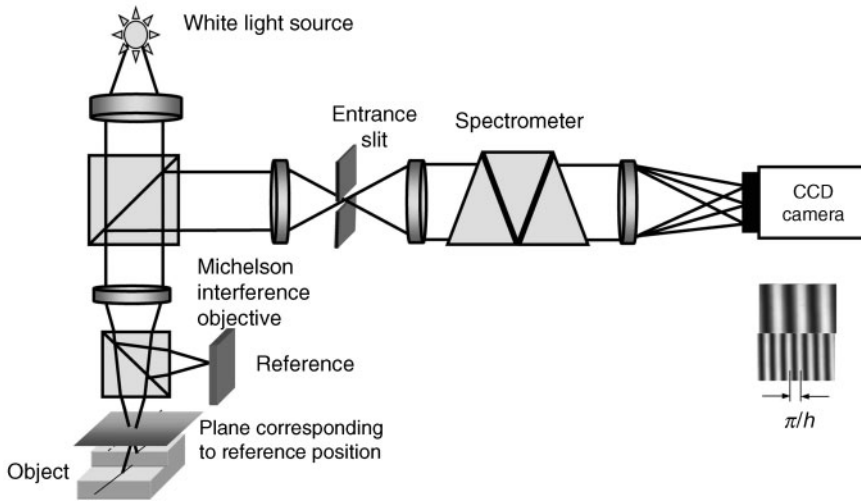


FIGURE 15.45. Schematic of a spectrally resolved white light interferometer.

purposes. Spectrally resolved white light fringes are used for many different applications like measuring the differential index of refraction, the index of refraction distribution, wavelength multiplexing, transmission of images, distance and displacement measurements and recently for profile measurement.

15.8.1. Image Buildup

In the spectrally resolved white light interferometer the chromatic axis is along one of the axes of CCD camera which is perpendicular to the slit of spectrometer. The row (or column) of CCD pixels registers a spectral interference signal from which the spectral phase or fringe frequency is calculated for a single object's point delivering information about the object's distance from the corresponding reference point, and one CCD frame delivers information about the profile of the object along one line as shown in Figure 15.46. Thus, the object needs to be scanned laterally in order to obtain a 3D profile.

A spectrally resolved white light interferometer with lateral scanning delivers the same type of fringes as a wavelength scanning interferometer so long as we think of the collected data as a cube (compare Figs. 15.40 and 15.47). The difference lies in the labeling of both cubes of data. In wavelength scanning interferometry (Fig. 15.40) one CCD frame delivers a monochromatic interferogram in spatial coordinates x, y . The third coordinate, the chromatic axis, follows interferograms that are registered in time during the scan of the source's wavelength. In spectrally resolved WLI, one CCD frame delivers spectral fringes in chromatic-spatial coordinates. The third coordinate, the spatial axis, follows interferograms registered in time during the lateral scan.

Like in wavelength scanning interferometry, the dynamic range for the measurement is limited by the spectral resolution of the spectrometer (equivalent to the tuning

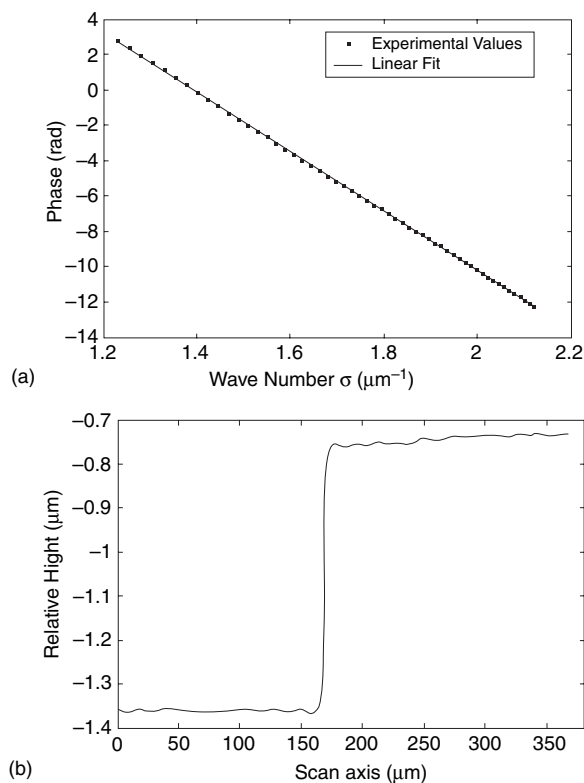


FIGURE 15.46. Obtained from spectrally resolved white light interferometer. (a) spectral phase along chromatic axis for one point on object and (b) profile of the step.

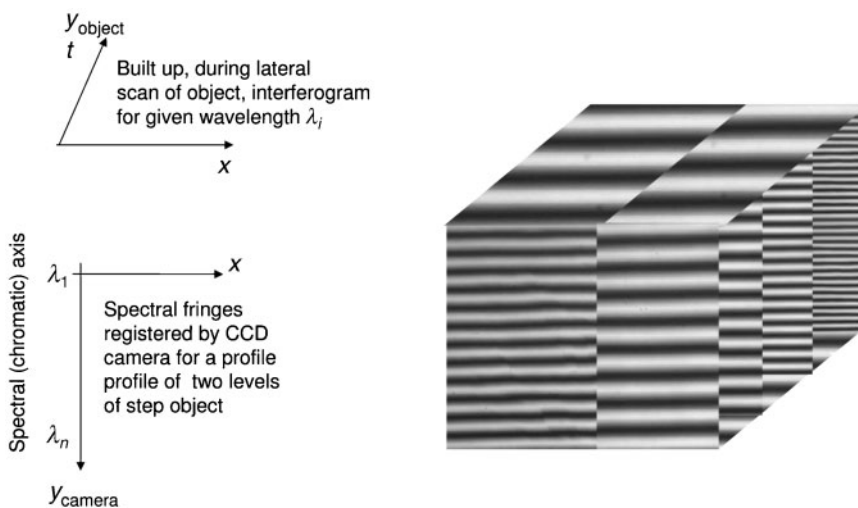


FIGURE 15.47. Cube of data in spectrally resolved interferometer for an object with step tilted with respect to the reference mirror around axis perpendicular to the step.

step in wavelength scanning interferometry), and the resolution is determined by the spectral bandwidth (tuning range) of the light source.

The chromatic axis of the CCD camera is calibrated typically with a cadmium (Cd) spectral lamp, which has four spectral lines, 643.8 nm, 508.6 nm, 480 nm, and 467.8 nm. These wavelengths are assigned to the corresponding pixels on the camera (see Fig. 15.48(a)). The wavelengths for the rest of the pixels are calibrated (see Fig. 15.48(b)) using Hartmann's formula.

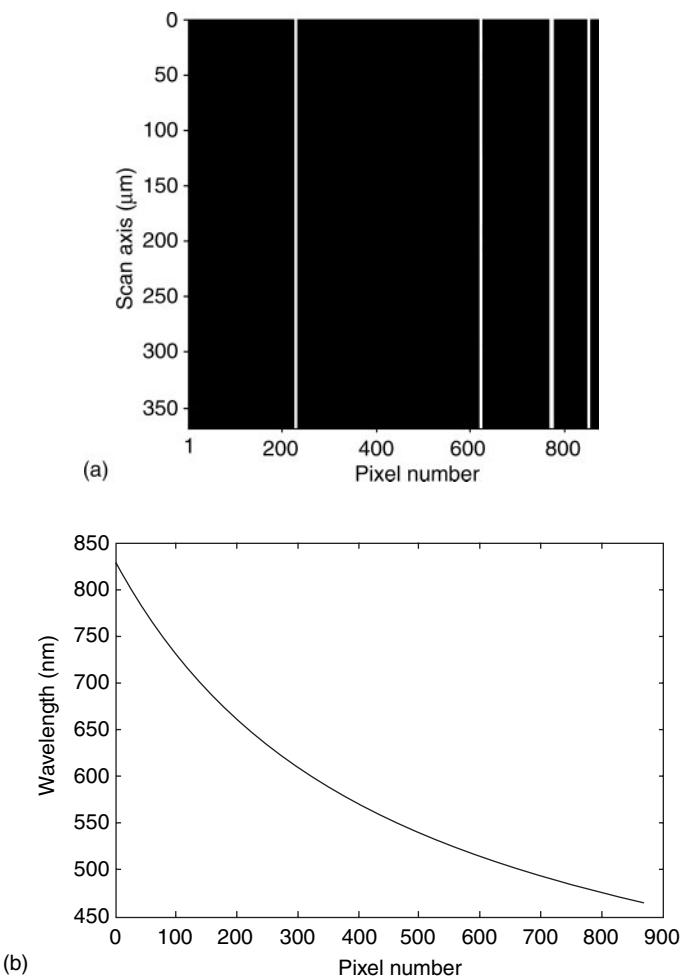


FIGURE 15.48. Calibration of chromatic axis of camera: (a) imaged spectrum of Cd lamp on the CCD and (b) calculated wavelength for each pixel. Reprinted with permission from Debnath and Kothiyal (2005).

15.8.2. Signal Analysis

In order to determine the distance of an object with respect to the reference plane, the spectral interferogram can be analyzed by measuring either the frequency of the fringes (as shown for wavelength scanning interferometry) or the spectral phase slope (Schwider and Zhou, 1994). Both methods require the carrier frequency of the fringes, which can be regulated by the distance of the object from the reference mirror. Spectral phase slope $\Delta\phi/2\Delta k$ can be measured using the Fourier Transform (Takeda and Yamamoto, 1994) or a spatial phase-shifting method (Sandoz, 1996). Although carrier methods require only a single frame, they do not distinguish the sign of the spectral phase slope. Like in the wavelength scanning interferometer, the sign of the spectral phase slope determines where the object is in relation to the reference mirror, either above it or below it, and this information is lost. In addition, carrier methods may be affected by the background irradiance variations of the object across the field.

In a spectrally resolved white light interferometer, PSI methods have been implemented to increase the resolution of the measured spectral phase and, thus, also the height, and at the same time to overcome some of these difficulties. PSI methods deliver information about the spectral phase slope, do not require fringes of carrier frequency, and are insensitive to spatial variations in background irradiance (Helen et al., 2001; Debnath and Kothiyal, 2005). With this method, points on the object in relative terms can be on either side of the reference mirror.

Thick and Thin Film Measurement. Spectrally resolved interferometry also can be used to measure film thicknesses as thin as 2 microns by mapping the peaks of the Fourier transform (Hausler and Lindner, 1998; Zuluaga and Richards-Kortum, 1999). The problems in this method, like in wavelength scanning interferometry, are ghost frequency peaks coming from multiple reflections of many interfaces and the inability of methods to distinguish the interface of the object as being above or below the reference mirror. Wojtkowski et al. (2002) suggested that using a PSI approach the position of the optical film interfaces can be determined without ambiguity. Recently Debnath et al. (2006) showed that the spectral phase calculated with a PSI method can measure engineering samples that have film thicknesses as thin as 100 nm. A spectrally resolved WLI approach allows for the simultaneous registration of the sample profile and film thickness.

15.8.3. Other Names for Spectral Interferometry

Spectrally resolved white light interferometry and wavelength scanning interferometry are often called spectral interferometry. Each of these methods also has been variously labeled. Spectrally resolved white light interferometry can be found in the literature as dispersive (white light) interferometry, white light channeled spectrum interferometry, or spatially resolved spectral interferometry. The wavelength scanning interferometer can also be called spectrally scanned interferometer, frequency scanning interferometer, wavelength tuning interferometer and optical frequency domain micromachinometer.

Variations of spectral interferometry are employed in the biomedical field; the term used there is frequency domain optical coherence tomography (FD-OCT). Whereas typical OCT is a point method and requires lateral scanning, FD-OCT works in the frequency domain, thus avoiding axial mechanical scanning. In the OCT field, both methods are commonly called frequency (or Fourier) domain optical coherence tomography (FD-OCT) or sometimes spectral radar.

15.9. POLARIZATION INTERFEROMETERS

In commercial interferometers the beam splitting is commonly done by amplitude splitting like in the Twyman–Green, Michelson or Fizeau interferometers; these systems were described in Section 15.4.1.1. Beam splitting can also be accomplished through the use of a polarizing beam splitter when different polarization states in the reference and object beams are required. These setups are called polarization interferometers and often utilize polarization techniques to introduce phase shifting between interfering wavefronts in order to avoid mechanical axial or wavelength depended phase shift. Such systems were described by Hettwer et al. (2000). Polarization technique for phase shifting will be described in Section 15.9.2.

Different type of polarization interferometers use polarizing beam splitter to split the incident beam into two sheared beams incident on the object; this technique creates a quasi-common path interferometer. Although the idea of the polarization interferometer was known at the turn of 20th century, these systems became popular when they were inserted into a microscope to create the differential interference contrast microscope (DIC). An excellent review of different types of polarization interferometers can be found in books by Françon and Mallick and by Pluta (Françon and Mallick, 1971; Pluta, 1993; Polarvarapu, 1997) and also in an article by Françon (1963). In addition, the previous edition of this book (Creath, 1989) details two other types of polarization interferometers, Sommargren (Sommargren, 1981) and Downs (Downs et al., 1985).

While imaging small features, on the order of illuminating wavelength and well below, in polarization interferometer it is important to understand how the reflected or transmitted wavefront is affected by illuminating beam state of polarization in order to interpret results correctly (Totzeck et al., 2005). To improve optical resolution of polarization interferometers, structure pupil filters are suggested to be used (Totzeck et al., 2002).

15.9.1. Differential Interference Contrast Microscope (Nomarski)

The DIC interferometer was invented, a Polish-born French physicist, Georges (Jerzy) Nomarski in 1955 (Nomarski, 1955) and is also called a polarization interference contrast microscope. In the Nomarski system, a typically broad source (like a halogen lamp) is used for illumination followed by a polarizer (see Fig. 15.49). This polarized light travels through the heart of the DIC microscope, which is a modified Wollaston birefringent prism pair – Nomarski prism. The Wollaston prism splits the

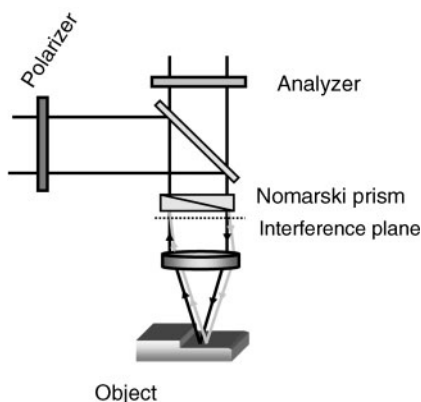


FIGURE 15.49. Differential interference microscope in reflection mode.

polarized light into two orthogonally polarized beams that travel at slightly different angles. Next, both beams are brought onto the object by the objective, and the object is illuminated with orthogonally polarized beams slightly sheared from each other. For this reason this interferometer is also called a shearing interferometer. This shear is on the order of tens to hundreds of nanometers, well below the resolution of the objective. Upon reflection two displaced beams travel back through the objective and are recombined by the Wollaston prism. To allow for observation of interference between both beams, an analyzer is placed before the beams reach the camera.

The interference pattern does not directly represent the shape of the image but rather its gradient in the direction of the shear introduced by the Wollaston prism. Thus, to fully characterize the object, an additional measurement at orthogonal shear needs to be taken, which is achieved by sample or optics rotation. The observed interference colors are phenomenal and give an effect of a pseudo three-dimensional appearance of the object. These colors can be varied by changing the amount of shear between beams via an axial shift of the Wollaston prism.

Initially, all DIC systems were manual and of a qualitative nature only. The user manually choose a Wollaston prism axial position so as to achieve an interference pattern that would be the most appealing and emphasize the features of the object that were under test. The most common type of DIC interferometer is used for qualitative observation of semitransparent biological samples; this system works in transmission and not on reflection. Although neither as popular nor as commercially available as white light interference microscopes, a DIC interferometer can also deliver quantitative data about a surface profile while working in reflective mode. Some idea about the optical path difference between sheared wavefronts can be achieved by looking at created interference colors and comparing them to Michel-Lévy and Lacroix who came up in 1889 with Interference Color Chart. A more reliable technique, one that does not require color comparison and can be used with a black and white CCD camera, is based on phase shifting interferometry (see chapter on Phase Shifting Interferometry

and Abdulhalim, 2001; Arnison et al., 2004). The phase shift between interfering beams can be obtained by shifting the Wollaston prism laterally or by rotating the polarizer. However, the phase shift will be wavelength dependent, and the fringes will change contrast during the phase shift. To avoid this changing contrast, achromatic phase shifting based on the geometric phase can be used (Hariharan, 1996). Once the optical path difference between sheared replica of the wavefront reflected from the object is obtained in two orthogonal directions, the original surface can be calculated. The advantage of the DIC interferometer is that it is almost insensitive to vibrations since they are almost common path interferometers. The major limitations of these interferometers, which include a short measurable depth and thickness of the object and index gradient, occur because of the limited depth of field of the objective like in any other non-scanning interference microscope. On the contrary, a very small depth of field for objectives with high NA can be utilized for optical sectioning if axial scan between object and objective is introduced. Reflective DIC are often used for quality inspection of integrated circuits in semiconductor industry. A lot of useful information about DIC interferometers working in reflection can be found on websites designed by for example Nikon and Olympus.

15.9.2. Geometric Phase Shifting

Many measurement techniques in interferometry involve shifting the phase of the interfering wavefronts. Mechanical phase shifters, when used in white-light and multiple-wavelength interferometry, introduce the same change in the optical path difference, measured in nanometers, for all wavelengths; however, the resulting phase shift, known as a dynamic phase shift, when measured in degrees or radians, varies with the wavelength. A different technique of phase shifting, involving a cycle of changes in the polarization of the light, can produce the same phase shift, measured in degrees or radians, for all wavelengths. This phase shift, known as the Pancharatnam phase (Pancharatnam, 1956), is a manifestation of the geometric phase (Berry, 1987), and it can generate any required wavelength-independent phase shift without a change in the optical path difference. As a result, geometric phase-shifting has found many applications in interferometry (Hariharan, 2005).

In white-light interference, a change in the geometric phase shifts the fringes under the coherence envelope (Hariharan et al., 1994), as shown in Figure 15.50, while the coherence envelope stays in place, resulting in no change in the fringe contrast at each point. In dynamic phase shifting, the whole white-light interferogram is shifted, resulting in changing fringe contrast at each point. With multiwavelength interferometry, a geometric phase-shifter will produce the same phase shifts for any wavelength used in the interferometer, without the need to make any changes in the phase shifter.

Achromatic phase-shifters operating on the geometric phase use circularly polarized light, as shown in Figure 15.51, and employ polarization elements such as a rotating half-wave plate followed by a quarter-wave plate and polarizer or, in a simpler arrangement, just a rotating polarizer. In order to introduce a phase shift between two interfering beams, the two beams need to be orthogonally polarized.

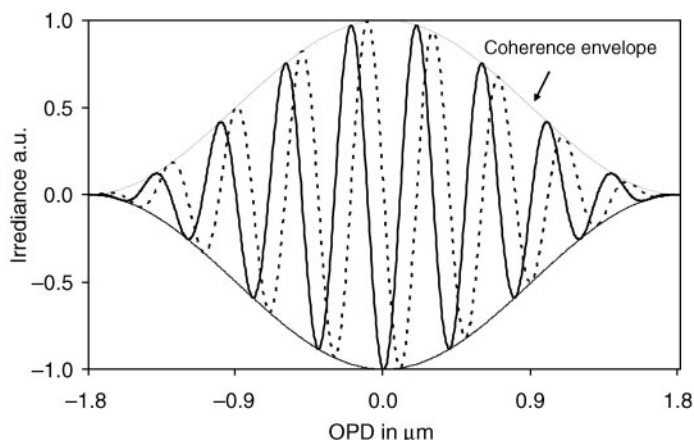


FIGURE 15.50. During achromatic phase shift only fringes shift, while envelope remains stationary.

Figure 15.52 shows an interferometer with two orthogonally linearly polarized beams leaving the reference and object arms of the interferometer. The geometric phase shifter, consisting of a rotating half-wave plate mounted between two quarter-wave plates with their axes set at 45° to the angles of polarization of the two beams (Hariharan and Ciddor, 1994; Hariharan et al., 1994), is placed at the exit of the interferometer. This interferometer employs the first type of geometric phase shifter shown in Figure 15.51a in which the first quarter-wave plate creates left- and right-handed circularly polarized beams. The half-wave plate then changes the right-handed circularly polarized beam to a left-handed one and the left-handed circularly polarized beam to a right-handed one. Finally, the second quarter-wave plate brings the two beams back to their original orthogonal linear polarizations. A rotation α of the half-wave plate shifts the phase of one linearly polarized beam by $+2\alpha$ and the phase of the other, orthogonally polarized beam by -2α , so that a net phase difference of 4α is introduced between the two beams. This phase difference is

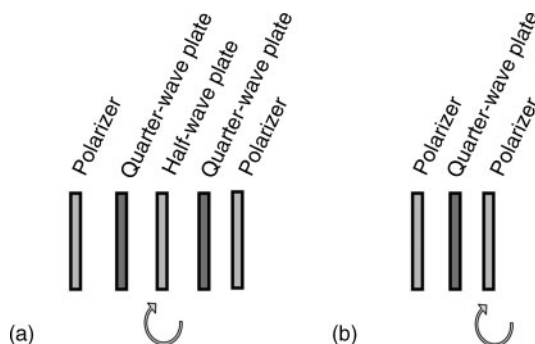


FIGURE 15.51. Geometric phase shifter with rotating (a) wave plate and (b) polarizer.

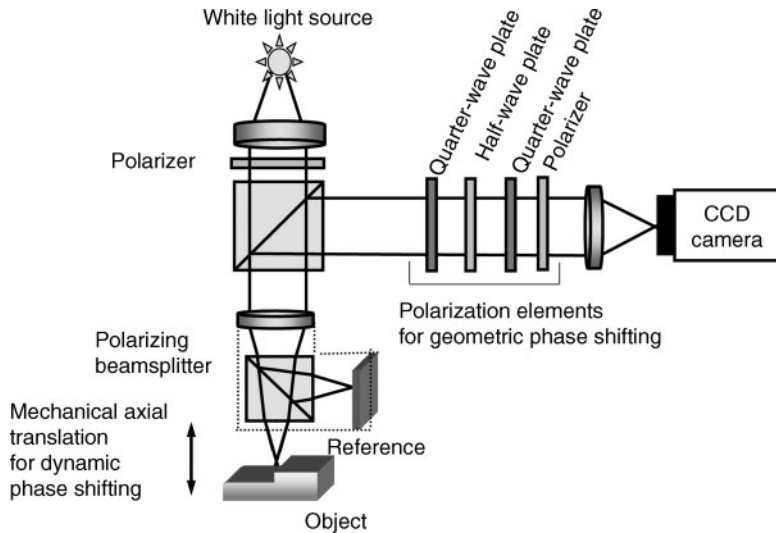


FIGURE 15.52. White light interference microscope with geometric phase shifting. At each position of the axial scan, approximately every 150 nm, geometrical phase shifting is introduced, and a few frames are collected to calculate the contrast of fringes.

very nearly independent of the wavelength over the whole visible spectrum. The polarizer makes it possible for the two beams to interfere.

The second type of geometric phase shifter shown in Figure 15.51b only requires a rotating polarizer to be placed after the quarter-wave plate that changes the two beams leaving the interferometer to left- and right-circularly polarized beams. In this case, if the test beam is left-circularly polarized and the reference beam is right-circularly polarized and both beams are incident upon the linear polarizer which is set at an angle α with respect to the x axis, both the test and reference beams, upon passing through the polarizer, become linearly polarized at an angle α . However, a phase offset $+\alpha$ is added to the test beam and a phase offset $-\alpha$ is added to the reference beam. A rotation of the linear polarizer by α therefore introduces a phase shift 2α between the two interfering beams. The linear polarizer acts as a phase shifting device and also makes it possible for these beams to interfere. While an achromatic quarter-wave plate could be used to extend the spectral range over which this phase-shifter operates, it turns out that the variations in the phase shift produced by this system due to variations in the retardation of the quarter-wave plate with the wavelength are quite small (Helen et al., 1998; Millerd et al., 2004).

The measurement time, which can be critical in some industrial applications, can be reduced if the interferograms are collected simultaneously. This can be done with the system presented in Figure 15.53 (Millerd et al., 2004). In this setup, a polarizing beamsplitter causes the reference and test beams to have orthogonal polarizations. Quarter-wave plates are placed in the reference and test beams so that the beam initially transmitted through the beamsplitter is reflected when it returns, and vice

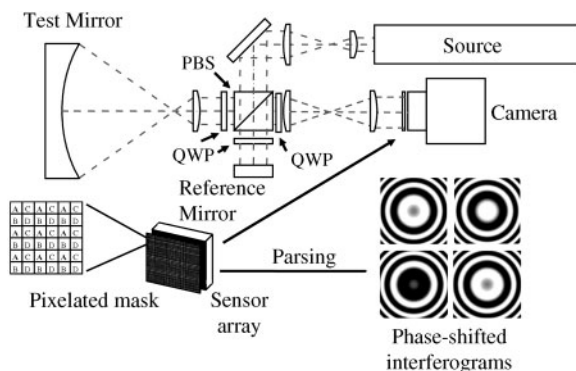


FIGURE 15.53. Simultaneous phase-shifting interferometer. (Courtesy 4D Technology).

versa. These two beams pass through a quarter-wave plate, which converts the two orthogonally polarized beams to right- and left-handed circularly polarized beams, and then through a phase mask. The quarter-wave plate can be placed at the exit of the interferometer, or in front of the camera, while the phase mask is placed just in front of the CCD array in the camera.

The phase mask is a micropolarizer array built up of groups of four linear polarizer elements having their transmission axes at 0° , 45° , 90° , and -45° as shown in Figure 15.54(a), or at 0° , 45° , -45° and 90° as shown in Figure 15.54(b), and is structured so that each polarizer element is placed over a detector element. These four linear polarizer elements introduce phase shifts between the test and reference beams of 0° , 90° , 180° , and 270° . Thus, four phase-shifted interferograms, obtained from each group of pixels (Fig. 15.54(c)), are recorded simultaneously using a single CCD array.

As can be seen, the phase mask works as a geometric phase shifter. The two essential requirements are that the test and reference beams have orthogonal polarizations, and the micropolarizer array matches the CCD array.

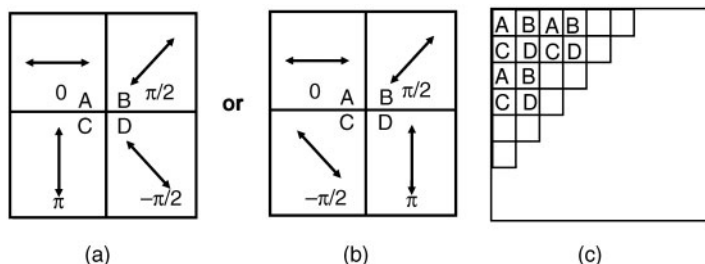


FIGURE 15.54. Phase filter. (a) 4 polarizer elements giving 0° , 90° , 180° , and -90° phase shifts; (b) 4 polarizer elements giving 0° , 90° , -90° , and 180° phase shifts, (c) phase filter made up of array of 4 polarizer elements. Courtesy 4D Technology.

15.10. OPTICAL RANGING METHODS

Optical ranging methods are typically single point methods used to measure for example length, distance, vibrations or index of refraction. They can be based on different principles; for example on geometry of light propagation used in laser triangulations or based on interferometric principles or on time measurement of light pulse flight. If scanning is employed all these methods can provide 3D measurement of the object. Single point methods are usually based on optical fibers and fast single point detectors. Some methods can and were made to be used with array detectors delivering information about ranging parallelly at multiple points to deliver information over the area without necessity of point by point scanning. Review of different methods for optical ranging was presented by Amann et al. (2001), Blais (2004), Chen et al. (2000), de Groot (2004), Friedman (2005), and Wagner and Hausler (2003). Selected papers on laser distance measurements were collected by Bosch and Lescure (1995).

15.10.1. Interferometric Ranging

Interferometric ranging is based on white light, two-wavelength, multiple wavelength, and spectral interferometer (Gerges et al., 1987; Smith and Dobson, 1989; Danielson and Boisrobert, 1991; de Groot and McGarvey, 1992; Haruna, et al., 1998; Bosch et al., 2001; Hariharan, 2003). Multiple wavelength interferometry was already used in 1989 to measure the length of an etalon (Michelson and Benoit, 1895) to overcome limitations of single wavelength interferometry. These methods evolved successfully into methods for very precise 3D profilometry described in this chapter.

Q2

15.10.2. Optical Triangulation

Triangulation sensors detect the backscattered light from a narrow laser beam impinging on an object (Dorsch et al., 1994). The reflected light is detected by a position sensitive device. From the change in position of the spot on the sensor the change in distance to the object can be determined. Laser scanning and slit scanning are based on optical triangulation. The principles of optical triangulation can be used in tactile profilometers like stylus profilometers and atomic force microscopes to detect the position of scanning probe.

15.10.3. Time of Flight (TOF)

These systems use light propagation as a measuring tool since the speed of light is one of the fundamental well-determined constants. Distance is measured by counting the time it takes for light to travel to an object and back. Time-of-flight method is a preferred method to measure long distances; this method was used to measure the distance to the moon. With the addition of a scanning system, aerial topographies can be obtained. The resolution of TOF measurements ranges from 0.3 mm to a few

centimeters or more. A good review of TOF systems was done by Blais (2004) and Moring et al. (1989)

15.11. SUMMARY

All of the methods described in this chapter allow for the measurement of topographies through various contact (tactile) and noncontact (optical) means. Oftentimes the needs of industry have pushed the development of methods that can extract particular information from a specific kind of sample in a unique environment. Testing MEMS devices, for example, with their irregular surfaces often present unique challenges, such as measuring laterally and vertically moving and deforming surfaces, where these measurements occur through a piece of glass that protects the sample. In addition, the need to reduce measurement times is always a priority.

Tactile methods have striven to develop long, narrow and smaller radius tips, lighter forces and new ways of tip motion so that a wider range of sample can be measured with higher precision and without damaging the sample. The interaction of AFM or SPM tips delivers an increasingly wider range of information about the electrical, magnetic and mechanical properties of different materials. However, since these techniques are point by point scanning techniques, decreasing measurement time is always crucial.

Optical methods continue to improve vertical resolution over a large range of height measurements. Recent trends show the development of techniques to measure more complex samples, those built of different materials or coated with transparent layers. Algorithms have been developed that obtain information about film thickness and profile measurement and correction due to phase change on reflection of different materials. In addition, new optical methods that are insensitive to vibrations are being developed to examine the topographies of very large objects.

We foresee that the current trends in developing new methods will continue to increase vertical and lateral range and resolution. Moreover, methods and systems continue to be modified to increase their application space. For example, foreseeable new applications include ways to measure samples submerged in liquids, in situ monitoring and measurement of difficult to reach areas, such as small millimeter-sized holes, are presently being developed. Finally, we envision a larger overlap with optical coherence tomography and confocal microscopy for measurement of biological specimens.

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