Combining multiple-subaperture and two-wavelength techniques to extend the measurement limits of an optical surface profiler

Eugene R. Cochran and Katherine Creath

A method has been developed for extending the measurement range of an optical surface profiler using the techniques for combining multiple subapertures and two-wavelength phase-shifting interferometry. The effective trace length of the optical profiler is augmented by making a series of partially overlapping collinear measurements and then piecing the subapertures into a composite profile, thus extending the field of view of the instrument. The vertical dynamic range of the optical profiler is extended by taking phase measurements at two wavelengths and then subtracting these measurements to obtain the same result as if the object had been tested at a longer equivalent wavelength. This allows the resolution of phase ambiguities that may exist when using single-wavelength phase-shifting interferometry. Combining these techniques offers numerous possible applications for testing deep wave fronts and surfaces, such as aspheric optical components, with variable sensitivity.

I. Introduction

One of the more favorable candidates for determining the microtopography of optical surfaces is the interference microscope. This instrument combines the basic functions of a microscope with those of an interferometer. The microscope, which provides a high numerical aperture and thus excellent resolving power, is modified to operate as an interferometer enabling the acquisition of phase information about the surface under examination. This phase information can easily be transformed into surface height information. Using phase-modulated interferometric techniques, it becomes possible to obtain very good vertical height resolution along with an excellent lateral resolution, which is provided by the microscope objective. Interference microscopes provide a quick, noncontact, and very repeatable way of obtaining quantitative surface height information.

Two major drawbacks of this instrument are (1) the limited field of view and (2) the finite vertical dynamic range. The field of view, or the measurement window of the instrument, is limited by the high numerical aperture of the microscope objective. The greater the numerical aperture of the system, the greater the resolving power and the smaller the measurement range. Thus there is a clear trade-off between resolving power and the length of a profile. The vertical dynamic range of this instrument is limited to surfaces whose slopes do not change the optical path difference between adjacent pixels by more than half of the measurement wavelength. (This corresponds to height changes of one quarterwave for reflection test configurations.) This constraint arises because phase-modulated interferometric techniques assume that the phase does not change by more than π between adjacent pixels.

To overcome these restrictions, the authors of this paper have applied the techniques for combining multiple subapertures or scans\(^1,2\) and two-wavelength phase-shifting interferometry\(^3-10\). The effective trace length of the optical profiler is augmented by making a series of partially overlapping collinear measurements. These individual scans are then concatenated by matching together the arbitrary piston and tilt errors introduced between measurements using a simple-least-squares fitting procedure. The vertical dynamic range of the optical profiler is extended by taking each individual subaperture measurement at two wavelengths and then subtracting the measurements at these two wavelengths. This provides the same result as if the object had been tested at a longer equivalent wavelength. As a result, it is possible to unwrap the phase where ambiguities existed before.

Combining these techniques offers numerous possible applications. Many situations originate in which step heights are greater than a quarter of a wavelength; structures of rough surfaces or steep slopes need to be
examined and measured over an extended region. Optical components such as gratings and waveguides may be considered in these categories. Geometries on integrated circuit components sometimes contain very large slopes that cannot be tested with conventional optical interference microscopes. However, these surfaces may be tested using the techniques outlined here. Machined surfaces are another area of application where these techniques would provide benefits.

II. Combining Multiple Subapertures

In a typical interference microscope an assortment of objectives may be employed providing an array of resolutions and profile lengths. The type of interferometer which is utilized depends on the objective magnification used. Generally, low power objectives use a Michelson configuration, medium power objectives use a Mirau configuration, and high power objectives use a Linnik configuration. Table I lists a variety of commercially available objective magnification options along with their associated parameters. Once the objective magnification of the microscope is set, the scan length of a single profile of the instrument is determined.

To augment the profile scan length of the instrument, a series of interferograms may be acquired over the region in which the examiner is interested. Each of these interferograms must be collinear with its previous subaperture, and each should be displaced by an amount so that an overlap exists between the successive subapertures. The overlap is necessary to adjust for the arbitrary piston and tilt discrepancies that occur between seams. Fig. 1 shows these arbitrary offsets for a composite profile of a photolithographic mask in which the pistons and tilts have not been matched between the successive data sets.

In this paper a simple serial approach is taken for piecing the subapertures together. This means that all data are corrected relative to the first subaperture in the set; consequentially, the first subaperture establishes the base line for the piston and tilt of the composite profile. More clearly stated, one first matches the second subaperture to the first subaperture, then the third subaperture is matched to the second corrected subaperture data set, etc. This process is continued until all subapertures have been corrected.

The method for determining the matching piston and tilt coefficients, $a_{i+1}$ and $m_{i+1}$, between subapertures is given by a simple least-squares minimization technique for the difference data in each overlap region:

$$y_{i+1}(x_j) = z_i(x_j) - z_i(x_j) = a_{i+1} + m_{i+1}x_j$$

where the coefficients are given by

$$a_{i+1} = \frac{1}{J} \left[ \sum_{j} x_j^2 \sum_{j} y_{i+1}(x_j) - \sum_{j} x_j \sum_{j} y_{i+1}^2(x_j) \right]$$

$$m_{i+1} = \frac{1}{J} \left[ \sum_{j} x_j y_{i+1}(x_j) - \sum_{j} x_j \sum_{j} y_{i+1}(x_j) \right]$$

$$\Delta = \left[ \sum_{j} x_j^2 \right]^{-1} \left[ \sum_{j} x_j \right]^2$$

and

$$x = \text{profile ordinate},$$

$$y = \text{profile height},$$

$$z = \text{height difference data in the overlap region between subapertures.}$$

Several options exist when combining the corrected series of subapertures into a composite profile. If the overlap between subapertures is greater than half of the individual subaperture length, at certain positions along the long-scan trace there is overlap between several neighboring subapertures. For this case it is possible to average all the corrected subaperture measurements that cover a specific spatial position. This would lead to a reduction in the inherent noise of a single subaperture measurement by $\sqrt{n}$, where $n$ is the number of subapertures at the specific spatial position. If the overlap between subapertures is less than half of the individual subaperture length, there is no overlap between neighboring subapertures, only between adjacent subapertures. For this case the composite profile is best represented by the corresponding corrected array segments. The second method will retain measurements that contain smaller accumulated piston

<table>
<thead>
<tr>
<th>MAGNIFICATION:</th>
<th>1.5X</th>
<th>2.5X</th>
<th>5X</th>
<th>10X</th>
<th>20X</th>
<th>40X</th>
<th>100X</th>
<th>150X</th>
<th>200X</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTERFEROMETER TYPE:</td>
<td>MICHELSON</td>
<td>MICHELSON</td>
<td>MICHELSON</td>
<td>MIRAU</td>
<td>MIRAU</td>
<td>MIRAU</td>
<td>LINNIK</td>
<td>LINNIK</td>
<td>LINNIK</td>
</tr>
<tr>
<td>PROFILE LENGTH:</td>
<td>8.87 mm</td>
<td>5.32 mm</td>
<td>2.66 mm</td>
<td>1.33 mm</td>
<td>0.666 mm</td>
<td>0.333 mm</td>
<td>0.133 mm</td>
<td>0.089 mm</td>
<td>0.067 mm</td>
</tr>
<tr>
<td>SPATIAL SAMPLING: INTERVAL</td>
<td>8.67 µm</td>
<td>5.20 µm</td>
<td>2.50 µm</td>
<td>1.31 µm</td>
<td>0.650 µm</td>
<td>0.325 µm</td>
<td>0.150 µm</td>
<td>0.087 µm</td>
<td>0.065 µm</td>
</tr>
<tr>
<td>WORKING DISTANCE:</td>
<td>11.5 mm</td>
<td>15 mm</td>
<td>1.5 mm</td>
<td>4.5 mm</td>
<td>2.5 mm</td>
<td>4.0 mm</td>
<td>1 mm</td>
<td>0.2 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>MAXIMUM SURFACE HEIGHTS:</td>
<td>7.92 µm</td>
<td>7.92 µm</td>
<td>7.92 µm</td>
<td>3.05 µm</td>
<td>1.95 µm</td>
<td>0.60 µm</td>
<td>0.54 µm</td>
<td>0.54 µm</td>
<td></td>
</tr>
<tr>
<td>MAXIMUM SURFACE SLOPES:</td>
<td>0.81 deg</td>
<td>1.34 deg</td>
<td>2.69 deg</td>
<td>5.37 deg</td>
<td>10.74 deg</td>
<td>21.49 deg</td>
<td>48.12 deg</td>
<td>53.85 deg</td>
<td>53.85 deg</td>
</tr>
</tbody>
</table>

15 May 1988 / Vol. 27, No. 10 / APPLIED OPTICS 1961
and tilt errors. In this paper the second approach is used because of its simpler and more straightforward implementation.

The primary error sources when piecing together a number of interferograms include the following: (1) lateral stage positioning; (2) detector array alignment; (3) defocus across the detector array; and (4) random noise. The stage can introduce positioning errors by a number of mechanisms, primarily hysteresis, backlash, and the drift of the zero location. If the stage positioning is not exact between subapertures, a shear between the overlapped data will introduce errors whose magnitude will be a function of the roughness of the surface under test. The linear detector array must be aligned precisely so that its orientation is parallel to the direction of the stage motion. If this is not the case, the overlap region between successive subapertures will not be correlated over a common data region.

If a defocus exists across the detector array, errors will be introduced because the last half of the first subaperture is matched to the first half of the second subaperture. Hence the same part of the object is sampled at different array pixels that have different defocus values. Random noise is primarily the result of thermal turbulence, electronic noise, and quantization errors. It is inherent in the system and cannot be eliminated. All these errors provoke the inaccurate determination of $a_{i+1}$ and $m_{i+1}$ for each subaperture. As a result of these inaccuracies, the composite profile will exhibit accumulated piston and tilt errors, which, by the serial nature of the algorithm, are smaller at the start and greater at the finish.

III. Two-Wavelength Techniques

Two-wavelength phase-shifting interferometry is a technique that extends the measurement range of single-wavelength phase-shifting interferometry. This technique has evolved from the coalescing of phase-shifting interferometry and two-wavelength holography. By combining these two techniques, the benefits of a larger phase measurement range than what is normally used with conventional phase-shifting interferometry and a higher measurement precision than what is normally possible using two-wavelength holography are gained.

The algorithms used for the calculation of phase in single-wavelength phase-modulated interferometry always involve solving for the arc tangent of an argument. As a result, the phase is measured modulo $2\pi$. To resolve the phase ambiguities that are a result of this method, an assumption must be made that the wavefront incident on the detector does not have an optical path difference greater than one-half of the measurement wavelength between adjacent pixels of the detector. This is equivalent to requiring less than one-half of a fringe or one-quarter of the measurement wavelength in surface height per pixel when the object is being tested in reflection. If the variations across the surface are greater than one-quarter of the measurement wavelength per pixel, it will be impossible to determine the fringe order numbers when trying to resolve the phase ambiguities because the data have not been sampled sufficiently. Two possible courses of action may be used to resolve these phase uncertainties; either a longer wavelength source, i.e., an IR source, may be used to test the surface, or two visible wavelengths may be used to synthesize a larger equivalent wavelength, so that the variations across the surface are less than one-quarter of the measurement wavelength.

One phase-modulated interferometry algorithm that can be used to extract phase, the four-bucket technique, was developed by Carré. By ramping the reference mirror with a piezoelectric transducer through a $2\pi$ phase change (usually near 90°), the instrument integrates the intensity into four frames or four buckets:

$A(x,y) = I_0[1 + \gamma \cos\{\phi(x,y) - 3\alpha\}]$

$B(x,y) = I_0[1 + \gamma \cos\{\phi(x,y) - \alpha\}]$

$C(x,y) = I_0[1 + \gamma \cos\{\phi(x,y) + \alpha\}]$

$D(x,y) = I_0[1 + \gamma \cos\{\phi(x,y) + 3\alpha\}]$

where $I_0$ is the average intensity, and $\gamma$ is the modulation of interference. The phase is calculated using the arctan relation

$\phi = \arctan \left[ \frac{(A - D) + (B - C)}{(B + C) - (A + D)} \right]$

for each array point. The calculation of the phase is independent of the actual amount the phase is shifted as long as it is linear and constant. This allows the same equations to be used at different wavelengths without changing the high voltage ramp to the PZT; i.e., recalibration of the instrument is not necessary. The virtues of phase-modulated interferometric algorithms, such as Carre's include: fast data acquisition, highly accurate phase measurements, data are obtained over a uniform array of points, results may be obtained with poor fringe contrast, and the technique is insensitive to intensity variations across the detector.

The two-wavelength algorithm involves subtracting the phase measurements taken at each of the test wavelengths,

$\phi_{eq}(x,y) = \frac{2\pi}{\lambda_{eq}} \text{OPD}(x,y) = \phi_a(x,y) - \phi_b(x,y)$

yielding the same result as if the measurement had been taken at an equivalent wavelength $\lambda_{eq} = (\lambda_a \lambda_b)/(\lambda_a - \lambda_b)$. The OPD in the above equation refers to the optical path difference between the wavefront that emerges from the test arm relative to the wavefront that emerges from the reference arm of the interferometer. In reference to the optical profiler used for this experiment, the optical path difference is proportional to twice the deviation in surface height between the test and reference surface, since each surface is tested in double pass. Hence surface height is given by
To remove $2\pi$ ambiguities from the equivalent wavelength data, the phase difference between two adjacent pixels of the equivalent phase must be less than $\pi$. $2\pi$ ambiguities are resolved or unwrapped after calculation of the equivalent phase by adding or subtracting multiples of $2\pi$ until the difference in phase between two adjacent pixels is less than $\pi$.

The equivalent wavelength data can be used to unwrap the phase of one of the single-wavelength measurements by determining the correct fringe orders. If the chromatic aberration of the objective is less than one-half of the measurement wavelength in optical path difference, direct comparison with the equivalent wavelength phase can be used to determine the phase ambiguities. The corrected phase is simply determined by comparing the equivalent wavelength phase $\phi_{eq}$ to the visible wavelength phase $\phi_{vis}$ and finding an integral number of $2\pi$ to add to $\phi_{vis}$. This extends the dynamic range of the shorter wavelength and increases the signal-to-noise ratio by $X_{eq}/X_{visible}$ of the equivalent wavelength measurement.\cite{12}

The sensitivity of this test may be tailored to any particular value by changing the two wavelengths employed. A list of equivalent wavelengths attainable for wavelengths used in this paper is shown in Table II.

The depth of focus of the microscope objective determines the vertical dynamic range for the two-wavelength technique when it is employed on an interference microscope. For the $10\times$ objective this distance is $\sim 10 \mu m$. Another fundamental limitation of this technique is determined by the ratio of the detector size to the fringe spacing. If too many fringes are incident on a single detector element, when the phase is shifted in the interferometer, the modulation at the single detector point will not be large enough for a measurement to be obtained. This is true because the detector averages the intensity across its area. So when large numbers of fringes are present and the phase is modulated, the intensity appears essentially constant to the detector. Low modulation points are discarded by data processing algorithms during calculations. To avoid this problem, the detector size must be smaller than the fringe spacing.

**IV. Implementation**

The surface profiler used in this study consists of several basic components: an interferometer; a microscope; a detector; interfacing electronics; and a computer. A schematic diagram of this phase-modulated interference microscope is shown in Fig. 2. The interferometer configuration is equivalent to that of a Mirau interferometer integrated into a package with a $10\times$ microscope objective that is attached to a piezoelectric transducer. The interferometer is drawn in Fig. 3. The detector used in this instrument is a 1024-element linear CCD array. The interfacing electronics coordinates the intensity data acquisition with the phase-shifting device (in this case a reference surface translated by a piezoelectric transducer) as well as transmitting the data to the computer. The computer, a Hewlett Packard model 330, contains an extensive software package that implements the phase modulation, two-wavelength, and multiple-subaperture algo-

<table>
<thead>
<tr>
<th>Wavelength ($\mu m$)</th>
<th>0.6117</th>
<th>0.6207</th>
<th>0.6335</th>
<th>0.6509</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6117</td>
<td>42.19</td>
<td>30.72</td>
<td>13.38</td>
<td></td>
</tr>
<tr>
<td>0.6207</td>
<td>42.19</td>
<td>30.72</td>
<td>13.38</td>
<td>23.70</td>
</tr>
<tr>
<td>0.6335</td>
<td>17.78</td>
<td>30.72</td>
<td></td>
<td>23.70</td>
</tr>
<tr>
<td>0.6509</td>
<td>10.16</td>
<td>13.38</td>
<td>23.70</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** Composite profile of a photolithographic mask without matching the piston and tilt between subapertures.

**Fig. 2.** Schematic diagram of the optical surface profiler.

**Fig. 3.** Optical schematic of a Mirau interferometer.
Fig. 4. Profile of a 1.3-μm deep grating measured 650.9 nm.

The procedure used when combining these two techniques is simple. First, the sample under test is placed on a computer-controlled stepper motor stage that contains an encoder enabling 0.1-μm lateral positioning resolution. The stage is used to move the sample between measurements allowing the acquisition of successive overlapping linear traces and thus the extension of the measurement range or the field of view. The measurement wavelength is dictated by a narrow-band interference filter positioned after a white-light source. The two-wavelength technique is incorporated by letting the computer take four frames of data at the first wavelength while shifting the phase in the interferometer. Next, the phase-shifting device is returned to its starting position, the narrowband filter is exchanged to the second wavelength, and four additional data frames are acquired while the phase is shifted. The phases for each wavelength are calculated modulo $2\pi$ and then subtracted to yield the equivalent wavelength phase modulo $2\pi$. An integration routine is then used to unwrap the phase ambiguities, and profile data for that subaperture are obtained. The stage is then incremented to the next position, data are acquired using the two-wavelength technique, and the stage is moved again in an iterative manner. This process continues until the desired profile length is obtained. Once the desired profile length has been obtained, the subaperture data for either the case of equivalent wavelength data or corrected single wavelength data are combined into one composite profile using the multiple-subaperture techniques. Once these data are compiled, the results are displayed in a variety of formats along with relevant statistical parameters. Surface profile, surface slope, power spectrum, and autocorrelation plots may also be displayed.

V. Results

Figures 4–10 show the results of this new technique for a gold-coated grating that has a modulation depth of 1.3 μm. The grating steps when measured at a single wavelength of 650.9 nm could not be determined since they are greater than one quarter of a wave in height (see Fig. 4). However, when two-wavelength and multiple-subaperture techniques are used, the results as shown in Fig. 5 are possible. In this profile a modulo-$2\pi$ phase at 611.7 nm is subtracted from a modulo-$2\pi$ phase at 650.9 nm for a number of subapertures. This gives subaperture profile data that are effectively measured at 10.1 μm. The nine subaperture profiles that have a 50% overlap between successive data files were combined using multiple-subaperture techniques.
The combination of these techniques enables the grating step heights to be determined unambiguously over an extended region. Figure 6 shows the repeatability of this technique to be ~16.2 nm rms. Figure 7 presents a long-scan profile composed of 611.7-nm wavelength subaperture profiles whose data have been corrected using the 10.1-\mu m equivalent wavelength profile data. This is done to reduce noise and to give the higher precision of the visible wavelength instead of that of the equivalent wavelength. Figure 8 shows corrected 620.7-nm wavelength profile data. Phase data for this trial were taken at 620.7- and 650.9-nm wavelengths giving an equivalent wavelength of 13.4. Figure 9 shows corrected 611.7-nm wavelength long-scan profile data. Phase data for this trial were taken at 611.7-nm and 633.5-nm wavelengths giving an equivalent wavelength of 17.8 \mu m. Last, in Fig. 10 a long-scan profile of corrected data similar to those in Fig. 5 is shown, except only seven files were connected, and an ~40% overlap was used. From these results it is easy to determine that both the two-wavelength and the multiple-subaperture prove to be effective in measuring this grating. The two-wavelength algorithm was tested with a variety of wavelength combinations revealing consistent results for all cases (Figs. 7–9). The multiple-subaperture algorithm proved its worthiness by demonstrating similar results when using different overlap sizes between subapertures (Figs. 7 and 10).

V. Conclusion

The data presented in this paper demonstrate the successful extension of both the horizontal and vertical dynamic ranges of an optical surface profiling instrument. The two-wavelength technique provides the mechanism to test steep surface features because of its ability to synthesize a longer equivalent wavelength that can be used to unwrap the phase ambiguities that exist when using single-wavelength techniques. The sensitivity of the vertical dynamic range is variable depending on the chosen wavelengths. The multiple-subaperture testing technique provides the mechanism to augment the scan length of the instrument and increase the instrument’s field of view. Combining these two techniques enhances the dynamic range of this instrument in both dimensions making the profiler a much more versatile instrument capable of measuring surfaces with steep slopes over larger regions. Experimental results presented in this paper demonstrate a fivefold gain in profile length coupled with ~80 times the gain in the vertical dynamic range.

References

system which also has access to information from reactor operators, finally producing a decision on the state of the reactor.

Other uses reported include document and schematic drawing analysis, 3-D reconstruction of the brain, gel electrophoresis, measuring geological fracture patterns, and recognizing patterns in cell motion.

Pattern recognition in Practice II will probably be of interest to specialists within this field, and others may have their appetites whetted by the applications presented. Be warned, however, that the majority of the optics community will need to invest a considerable effort before a deep understanding of much of this material is achieved.

ROBIN STRICKLAND


Although phonon physics is the oldest branch of condensed matter physics, there is a lot of life still left in this field, as this book makes clear. It is concerned with seven areas of condensed matter physics in which phonons play a significant role and which are generally treated only sketchily, if at all, in existing treatises on phonons. These are piezoelectricity, ferroelectricity (written with J. A. Anderson's fascinating article "Psychological Implications of Parallel Systems" that appeared in the Apr. 1986 issue describing one very simple form of an elegant artificial neural network. Alkon's book gives insight into reasons for the performance gap.

In eighteen closely reasoned and beautifully written short chapters the reader (who is presumed to have no prior knowledge of neurobiology) is introduced to the properties of biological neurons, the interrelation of neurons and neural networks in simple animals, the signals exchanged among neurons, the changes that occur in neurons when the animal learns, and the differences between molluscan and vertebrate neurons and brains. The last few chapters build plausible models based on the nature of synapses in molluscan and mammalian systems. Each step in building this unified explanation of learning, storage, and recall is explained with the help of clear descriptions of biophysical experiments that are illustrated with line drawings and micrographs. The exposition focuses on the observed changes in neurons and their membranes—changes that are the basis of the phenomena called associative learning. What is being described is the arduous but fascinating process of elucidating the first biological neural network with demonstrated learning capability, explicating its wiring diagram, and demonstrating the neural interconnections and cellular mechanisms specifically responsible for learning. The reader will be particularly impressed by the absence of speculation unsupported by experimental data. The chapter on ion channels in cell membranes is the only one that someone untrained in neurobiology may find hard going.

The author makes a strong case that the cellular mechanisms of memory have been conserved in the evolutionary process and can be observed in invertebrates and vertebrates alike. An understanding of these mechanisms will undoubtedly play an important part in future expansion of the power and scope of synthetic neural networks, be they electronic or optical. After finishing this book, you will want to share it with all your friends; reading it is a stimulating and delightful experience.

THOMAS P. VOGL

continued on page 1991