

# Step height measurement using two-wavelength phase-shifting interferometry

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Two-wavelength phase-shifting interferometry is applied to an interference phase-measuring microscope enabling the measurement of step features. The surface is effectively tested at a synthesized equivalent wavelength  $\lambda_{eq} = \lambda_a \lambda_b / |\lambda_a - \lambda_b|$  by subtracting phase measurements made at visible wavelengths  $\lambda_a$  and  $\lambda_b$ . The rms repeatability of the technique is  $\lambda/1000$  at the equivalent wavelength. To improve the precision of the data, the phase ambiguities in the single-wavelength data are removed using the equivalent wavelength results to determine fringe orders. When this correction is made, a measurement dynamic range (feature height/rms repeatability) of  $10^4$  is obtainable. Results using this technique are shown for the measurement of an optical waveguide and a deeply modulated grating.

## I. Introduction

Phase-measurement techniques at a single wavelength have the built-in assumption that the wavefront incident on the detector array does not change by more than one-half of the measurement wavelength between adjacent detector elements. This is equivalent to requiring less than one-half of a fringe per detector spacing or one-quarter of the measurement wavelength in surface height change between adjacent pixels when testing a surface in reflection. The problem in measuring step heights using an optical profiler is determining fringe-order numbers when removing phase ambiguities because the phase cannot be sampled sufficiently across the discontinuity. The left side of Fig. 1 shows a step whose height is greater than a quarter of a wavelength. On the right is a possible fringe pattern for this step. Given this information, we do not know how to match the fringe-order numbers on the two sides of the discontinuity. Figure 2(a) shows a black and white photograph of white light fringes for a step where it is obvious that this step is more than a couple of fringes high. As soon as a narrow bandpass filter is introduced to define the measurement wavelength as shown in Fig. 2(b), the fringe orders become ambiguous, and the height of the step cannot be determined at this wavelength.

To determine the step height in the example of Fig. 1, the optical profiler measurement can be desensitized by creating a beat wavelength from two measurements at shorter wavelengths. This solution is shown in Fig. 3. Measurements are made at  $\lambda_a$  and  $\lambda_b$  yielding fringe orders  $m$  and  $n$ . When these measurements are combined, the result is as if the surface had been measured at a longer  $\lambda_{eq}$  giving fringe order numbers  $p$ . This technique is known as two-wavelength phase-shifting interferometry.<sup>1-5</sup> Using this technique along with correcting ambiguities in the single-wavelength data, the dynamic range of an optical profiler can be extended without sacrificing its high measurement precision.

The upper limit to the height ranges which can be measured is dictated mostly by the depth of focus of the objective being used. The ultimate height limit depends on the temporal and spatial coherence of the source. With the 10X microscope objective used in these examples, the measurement range is limited to  $\pm 5 \mu\text{m}$ . Many kinds of sample easily fall within this range which are not measurable using a single wavelength. Applications of this technique include the measurement of steep slopes, step heights, and rough surfaces. This paper explains the two-wavelength technique for measuring step heights and shows the results of testing step features in an optical waveguide and a grating.

## II. Theory

Phase-shifting interferometry is a well-known technique which has been used with great success in optical profilers.<sup>6,7</sup> For the calculations in this paper, an algorithm developed by Carré is used.<sup>8</sup> This algorithm calculates the phase independent of the amount of phase shift so that the profiler does not need recalibra-

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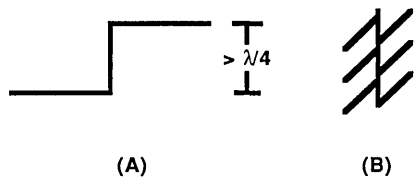


Fig. 1. (A) Step height too large to measure with a single wavelength  $\lambda$ . (B) Fringes in region of step show possible ambiguity in fringe order.

tion each time the wavelength is changed. The phase information is obtained by shifting the phase of one beam in the interferometer by a known amount and measuring the intensity in the interferogram for many different phase shifts. The intensity for each data frame is integrated over the time it takes to move a reference mirror linearly through a  $2\alpha$  change in phase (usually near  $90^\circ$ ) with a piezoelectric transducer (PZT). Four frames of intensity data are recorded in this manner:

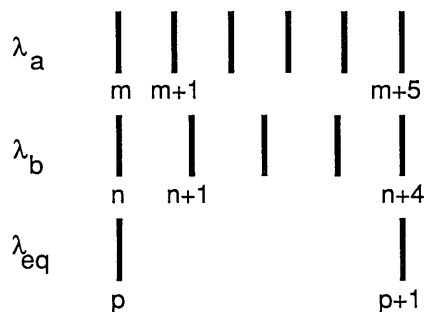


Fig. 3. Synthesis of beat wavelength  $\lambda_{eq}$  using shorter wavelengths  $\lambda_a$  and  $\lambda_b$ .

$$\begin{aligned} A(x,y) &= I_0[1 + \gamma \cos[\phi(x,y) - 3\alpha]]; \\ B(x,y) &= I_0[1 + \gamma \cos[\phi(x,y) - \alpha]]; \\ C(x,y) &= I_0[1 + \gamma \cos[\phi(x,y) + \alpha]]; \\ D(x,y) &= I_0[1 + \gamma \cos[\phi(x,y) + 3\alpha]]; \end{aligned} \quad (1)$$

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

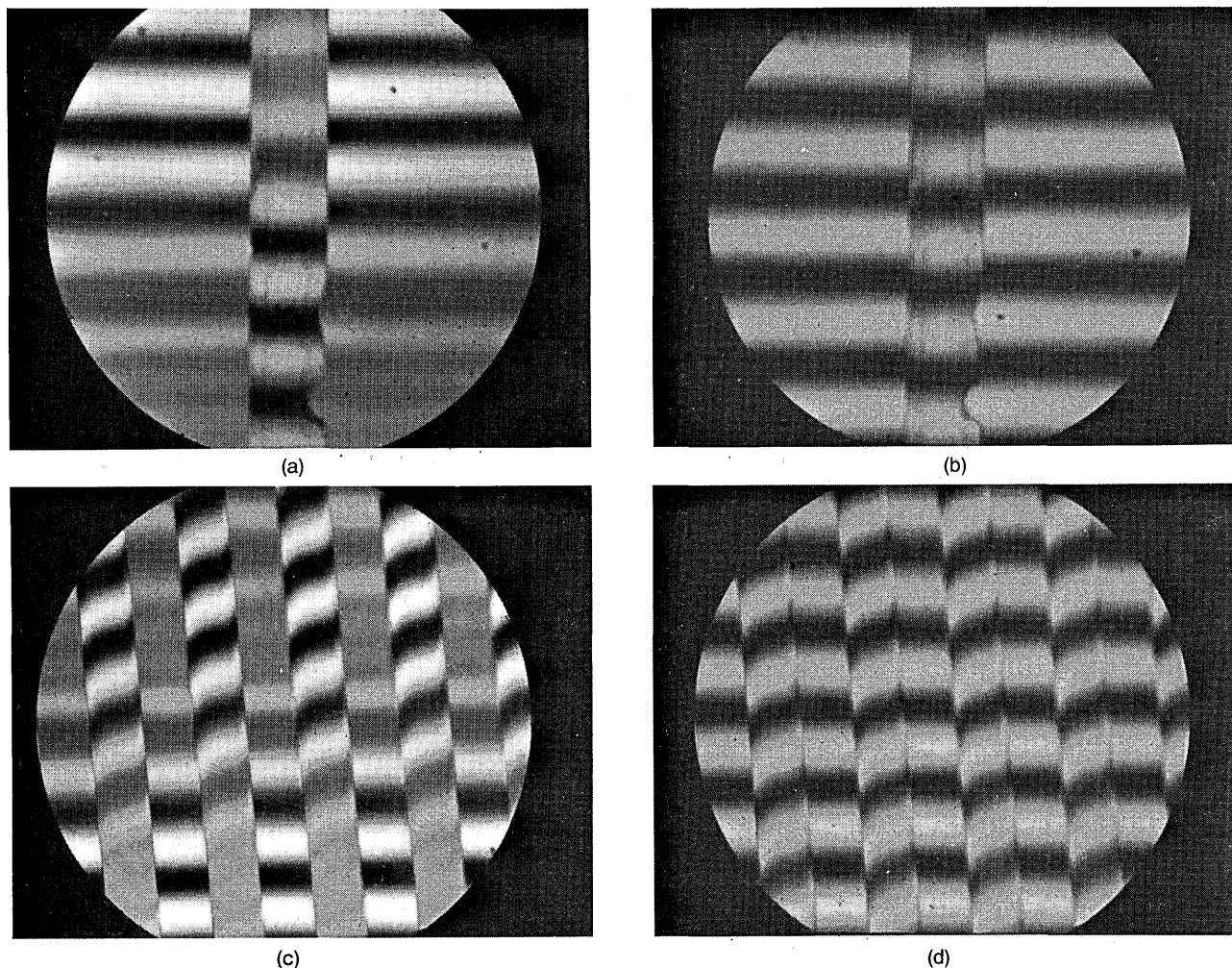


Fig. 2. Black and white photographs of (A) white light fringes of an optical waveguide, (B) same fringes with a narrowband filter in place, (C) white light fringes of a grating, and (D) fringes of grating with narrowband filter in place.

$$\phi = \tan^{-1} \left\{ \frac{\sqrt{[(A-D) + (B-C)][3(B-C) - (A-D)]}}{(B+C) - (A+D)} \right\} \quad (2)$$

at each detected point in the interferogram. The calculation of the phase is independent of the actual amount the phase is shifted as long as  $\alpha$  is linear and constant.

Extension of the measurement range of phase-shifting interferometry over a larger dynamic range is obtained by subtracting measurements taken at two different wavelengths<sup>3</sup>:

$$\phi_{eq}(x,y) = \frac{2\pi OPD(x,y)}{\lambda_{eq}} = \phi_a(x,y) - \phi_b(x,y), \quad (3)$$

where  $\phi_a$  and  $\phi_b$  are the phases measured for  $\lambda_a$  and  $\lambda_b$ . The difference in the phases measured at the two wavelengths yields the phase associated with an equivalent wavelength  $\lambda_{eq}$ . Results from a test using Eq. (3) are the same as if the surface were measured using an equivalent wavelength:

$$\lambda_{eq} = \frac{\lambda_a \lambda_b}{|\lambda_a - \lambda_b|}. \quad (4)$$

OPD in Eq. (3) refers to the optical path difference between the wavefront reflected off the test surface and reference surface. In the case of the optical profiler, the OPD is twice the difference between the test surface and reference surface. Thus the surface height is given by

$$H(x,y) = \frac{1}{2} \left[ \frac{\phi_{eq}(x,y) \lambda_{eq}}{2\pi} \right]. \quad (5)$$

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  $\pi$  ( $\lambda_{eq}/2$  in OPD,  $\lambda_{eq}/4$  on the test surface).  $2\pi$  phase ambiguities are smoothed after subtracting the two measured phases by comparing adjacent pixels and adding or subtracting multiples of  $2\pi$  until the difference between adjacent pixels is  $< \pi$ . The wavefront's phase between adjacent pixels must not change by more than  $\pi$  (one-half wave of OPD) at the equivalent wavelength for the  $2\pi$  ambiguities to be handled correctly. The sensitivity of the test can be varied by changing the two illuminating wavelengths.

To measure the phase at an effective wavelength  $\lambda_{eq}$  using two shorter wavelengths under computer control, the following algorithm is used. First, the computer takes four frames of data at  $\lambda_a$  while shifting the phase in the interferometer. Next, the phase shifter is returned to its original position, the illumination is switched from  $\lambda_a$  to  $\lambda_b$ , and four more data frames are taken while shifting the phase the same as for  $\lambda_a$ . The phases  $\phi_a$  and  $\phi_b$  are calculated modulo  $2\pi$  using Eq. (2) and then subtracted to yield  $\phi_{eq}$  modulo  $2\pi$ . Phase ambiguities are then removed using an integration routine, and surface height data are calculated using Eq. (5). This approach is very simple and easily implemented using existing phase-measurement optical profilers.

There is a reduction in signal-to-noise ratio (SNR) at the equivalent wavelength relative to the smaller

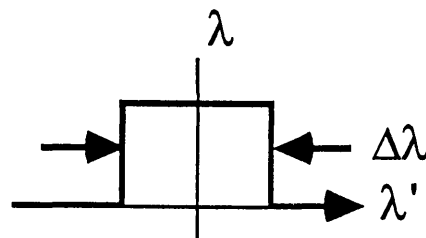


Fig. 4. Wavelength bandpass used for calculation in Eq. (6).

measurement wavelengths because the SNR is wavelength dependent.<sup>1,5</sup> This scaling is referred to as an error magnification and is proportional to the ratio of the two wavelengths. Thus a SNR of 1000 at  $0.5 \mu\text{m}$  becomes a SNR of 50 at  $10 \mu\text{m}$ .

The equivalent wavelength data can be used to remove ambiguities in one of the single-wavelength phase measurements by determining the correct fringe orders.<sup>1</sup> As long as the noise in the equivalent wavelength phase is less than one-half of the visible measurement wavelength in OPD, the number of  $2\pi$  terms to add to the single-wavelength measurement can be determined by direct point-by-point comparison with the integrated equivalent-wavelength phase. A corrected phase is simply determined by comparing  $(\lambda_{eq}/\lambda_{vis})\phi_{eq}$  to  $\phi_{vis}$  and finding an integral number of  $2\pi$  terms to add to  $\phi_{vis}$ . This correction extends the dynamic range of the shorter visible wavelength and increases the SNR of the measurement by the ratio  $\lambda_{eq}/\lambda_{vis}$  over the equivalent wavelength measurement.

Since the optical profiler used in this work uses narrowband illumination, the effects of the source's wavelength bandwidth need to be determined. Assuming a wavelength spread as shown in Fig. 4, the intensity in the interferogram can be written as

$$I = \frac{1}{\Delta\lambda} \int_{\lambda-\Delta\lambda/2}^{\lambda+\Delta\lambda/2} I_0 \left[ 1 + \gamma \cos \left( \frac{2\pi OPD}{\lambda'} \right) \right] d\lambda', \quad (6)$$

where  $\Delta\lambda$  is the wavelength bandwidth and  $\lambda$  is the average wavelength. When  $\Delta\lambda^2 \ll \lambda^2$ , evaluation of this integral yields

$$I = I_0 \left[ 1 + \gamma \operatorname{sinc} \left( \frac{\pi OPD}{\delta_c} \right) \cos \left( \frac{2\pi OPD}{\lambda} \right) \right], \quad (7)$$

where  $\operatorname{sinc}(x) = \sin(x)/x$ , and the coherence length  $\delta_c$  is defined as  $\lambda^2/\Delta\lambda$ . The only effect of integrating over the wavelength bandwidth is to reduce the modulation of the interference fringes by the sinc factor. Otherwise, the interference fringes are defined at the average wavelength. If we assume a wavelength  $\lambda$  of 600 nm and a wavelength bandwidth  $\Delta\lambda$  of 10 nm, the coherence length is  $36 \mu\text{m}$ , the modulation is reduced to 0.99 for an OPD of  $1 \mu\text{m}$ . For a bandwidth of 100 nm, the modulation is reduced to 0.88. A plot of fringe modulation (contrast) vs wavelength bandwidth for different OPD values is shown in Fig. 5.

Even though the wavelength bandwidth does not affect the measurement, the average or effective wavelength of the source may cause errors because the equivalent wavelength is very dependent on the differ-

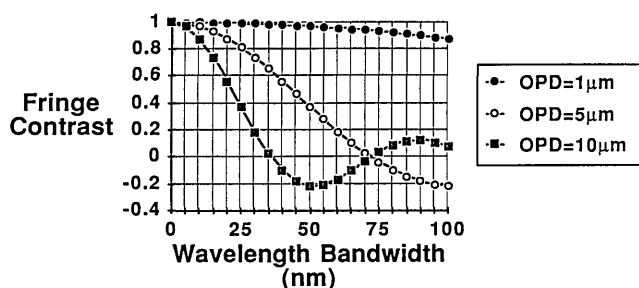


Fig. 5. Fringe contrast vs wavelength bandwidth for different OPDs using  $\text{sinc}(\pi\text{OPD}/\delta_c)$  terms of Eq. (7) at 600 nm.

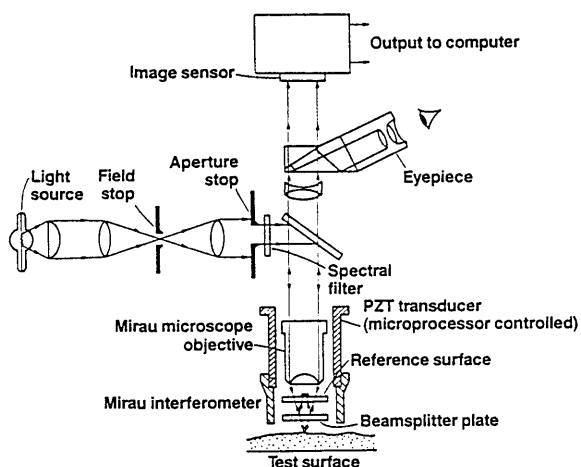


Fig. 6. Schematic of optical profiler using a Mirau interferometer.

ence between the two measurement wavelengths. An error of 1 nm in wavelength for sources at 600 and 630 nm yields an equivalent wavelength of  $12.6 \mu\text{m}$  with an error of  $\pm 0.42 \mu\text{m}$ . If the phase ambiguities in the single-wavelength data are corrected using the equivalent wavelength data as described above, errors due to the difference in the wavelengths do not matter. Thus it is best to use the equivalent wavelength data only as a way to reconstruct the wavefront made at a single wavelength.

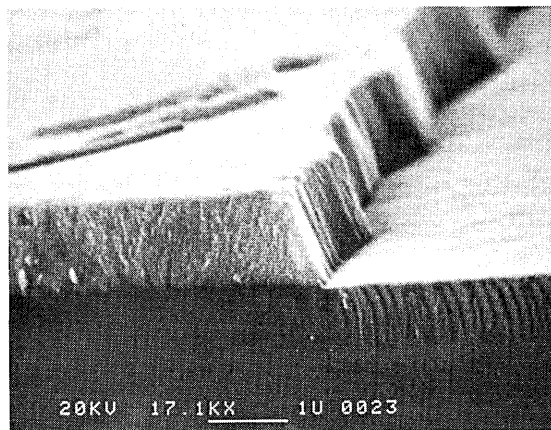
Finally, to measure step heights accurately, the sample must have the same material on both sides of the step providing the same phase change on reflection. If different materials are on opposite sides of the step, the height will not be correct unless the phase change on reflection for both materials is taken into account.

### III. Experiment

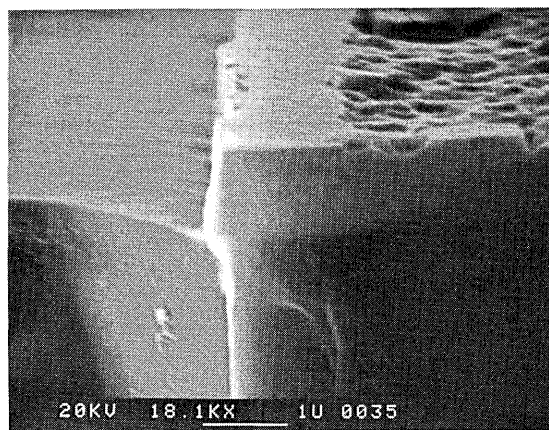
Figure 6 shows the optical layout for the optical profiler used in these experiments. It consists of a Mirau interferometer attached to an optical microscope. A PZT is used to shift the reference surface relative to the test surface producing an intensity modulation which is measured using a 1024-element Fairchild linear detector array. The measurement wavelength is determined by a narrowband interference filter placed in front of the white light source. The filters used in this paper had 10-nm bandwidths with

Table I. Equivalent Wavelengths Using 10 nm Bandpass Interference Filters

$\lambda_{\text{eq}} (\mu\text{m})$	0.6509	0.6316	0.6117	0.5774
0.6509	—	21.30	10.16	5.11
0.6316	21.30	—	19.41	6.73
0.6117	10.16	19.41	—	10.30
0.5774	5.11	6.73	10.30	—



(a)



(b)

Fig. 7. Scanning electron micrographs of 1- $\mu\text{m}$  high step in optical waveguide.

center wavelengths at 650.9, 631.6, 611.7, and 577.4 nm. The equivalent wavelengths possible using this filter set are shown in Table I. The chromatic aberration of this system is found to be within the noise of the measurement by scaling and subtracting surface height measurements taken at different wavelengths. A 10X objective is used for all measurements.

The first object tested is an optical waveguide consisting of a 1- $\mu\text{m}$  high nickel stripe on a silicon substrate overcoated with a thin layer of gold. Scanning electron micrographs of this feature are shown in Fig. 7, and photographs of the fringes are shown in Figs. 2(a) and (b). Figures 8(A) and (B) show measure-

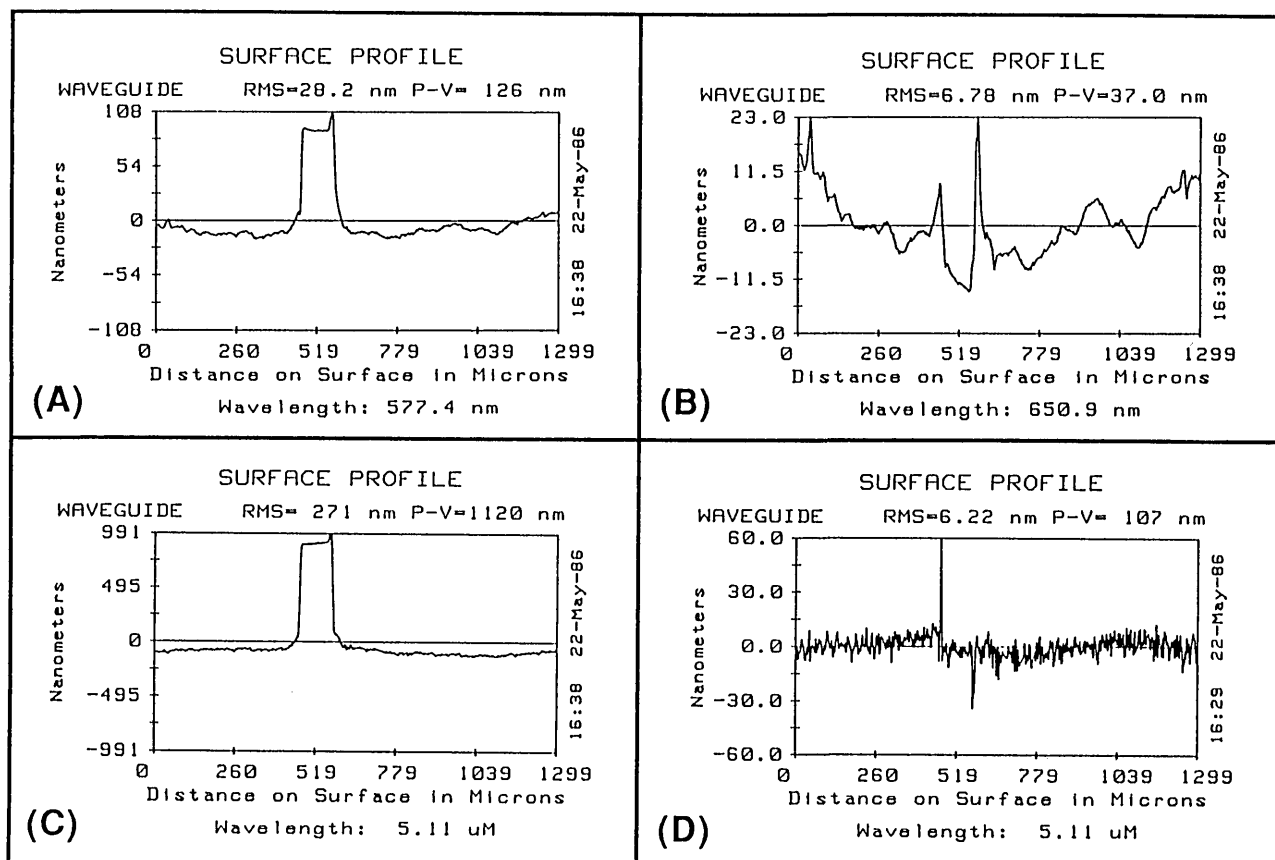


Fig. 8. Profile of optical waveguide at (A) 650.9 nm and (B) 577.4 nm where step is incorrect. (C) Profile combining measurements of (A) and (B) to obtain correct step ( $\lambda_{eq} = 5.11 \mu\text{m}$ ). (D) Repeatability of 5.11- $\mu\text{m}$  measurement.

ments made at 650.9 and 577.4 nm. These profiles show that the steps in the grating could not be determined because they are  $>\lambda/4$ . When the modulo- $2\pi$  phase at 577.4 nm is subtracted from the modulo- $2\pi$  phase at 650.9 nm, the result is the profile in Fig. 8(C), which is effectively measured at 5.11  $\mu\text{m}$ . In this case the step heights can be determined unambiguously. When the test is repeated on the same location of the grating, the difference between two sets of data at 5.11  $\mu\text{m}$  shows an rms of 6 nm, which is  $\lambda/800$  [shown in Fig. 8(D)].

Next a gold-overcoated grating with a modulation depth of 1.3  $\mu\text{m}$  is measured. Photographs of interference fringes taken through the microscope are shown in Figs. 2(c) and (d). Figure 9(A) shows the measurement made at 650.9  $\mu\text{m}$ , which does not resemble a square grating. When this measurement is combined with one made at 611.7 nm, the grating is correctly represented at 10.16  $\mu\text{m}$  in Fig. 9(B). This measurement has an rms repeatability of  $\lambda/1400$  [see Fig. 9(C)]. A measurement at an equivalent wavelength of 19.41  $\mu\text{m}$  (combining 631.6 and 611.7 nm) shown in Fig. 9(D) has the same step height as measured at 10.16  $\mu\text{m}$  but is noisier because of the SNR scaling.

To improve the noise in the measurement, the profile at 10.16  $\mu\text{m}$  is used to remove the ambiguities in the 650.9-nm profile of Fig. 9(A). The corrected profile is

shown in Fig. 10(A). It is noticeably less noisy than Fig. 9(B) and shows the same step height. The difference between two corrected measurements taken at 650.9 nm shows an rms measurement repeatability of 0.35 nm (or  $\lambda/230$ ) shown in Fig. 10(B). This means the step height of 1.3  $\mu\text{m}$  is measurable to a precision of 0.35 nm yielding a dynamic range of 3700. Using the equivalent wavelength data to determine fringe order increases the measurement precision by the ratio of the wavelengths.

#### IV. Conclusions

Two-wavelength techniques are very valuable for the testing of steep surfaces such as steps because of the variable measurement sensitivity attainable by changing wavelengths. The technique presented in this paper is very straightforward and easy to implement. The wavelength bandwidth of a source used in phase-measurement interferometry only affects the fringe modulation, whereas the difference between the two visible wavelengths may cause errors in determination of the step height because the equivalent wavelength is very sensitive to this difference. To increase the precision of the two-wavelength measurement and reduce errors due to uncertainties in the difference of the measurement wavelengths, the single-wavelength phase data are corrected for  $2\pi$  ambiguities using the

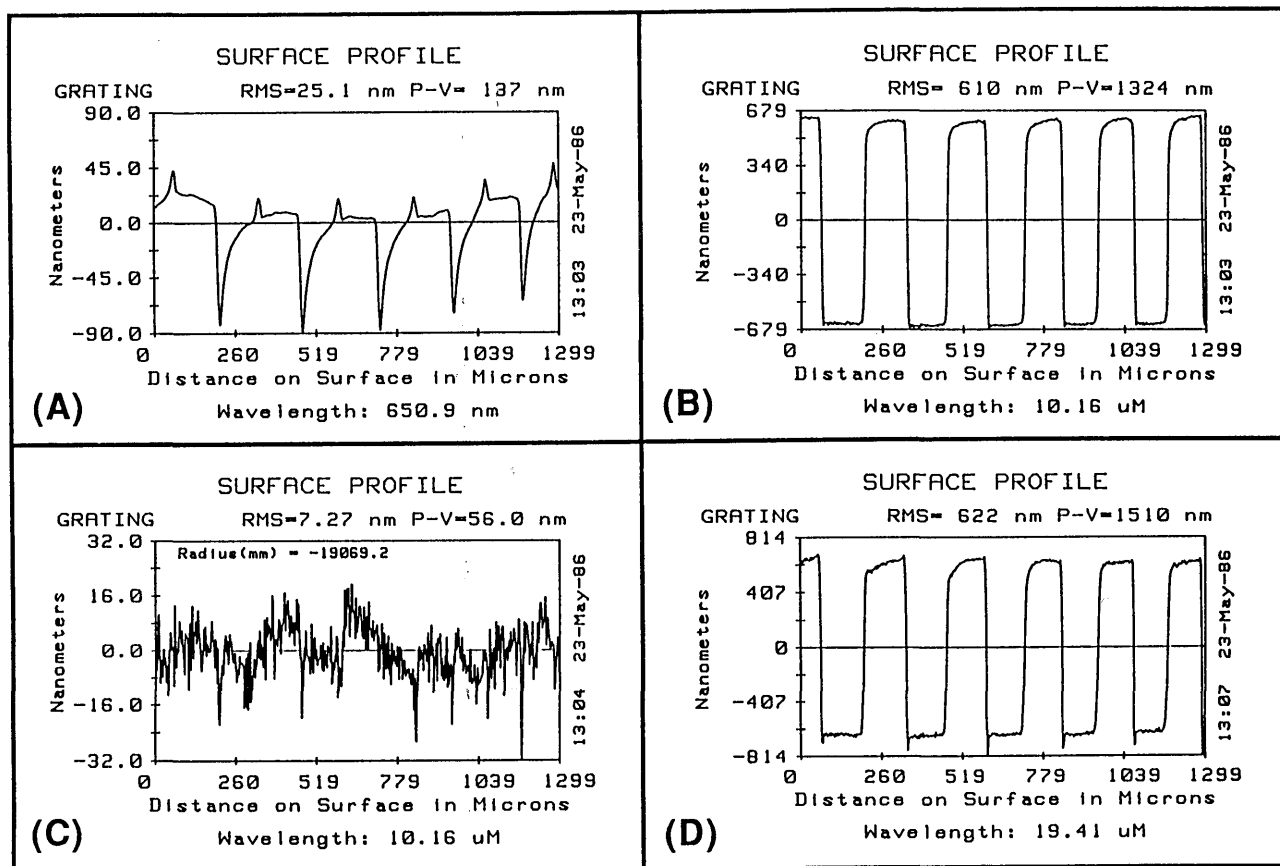


Fig. 9. (A) Profile at 650.9 nm does not resemble a square grating. (B) Profile of grating at equivalent wavelength of 10.16  $\mu\text{m}$ . (C) Repeatability of 10.16- $\mu\text{m}$  measurement. (D) Profile of grating at 19.41  $\mu\text{m}$ .

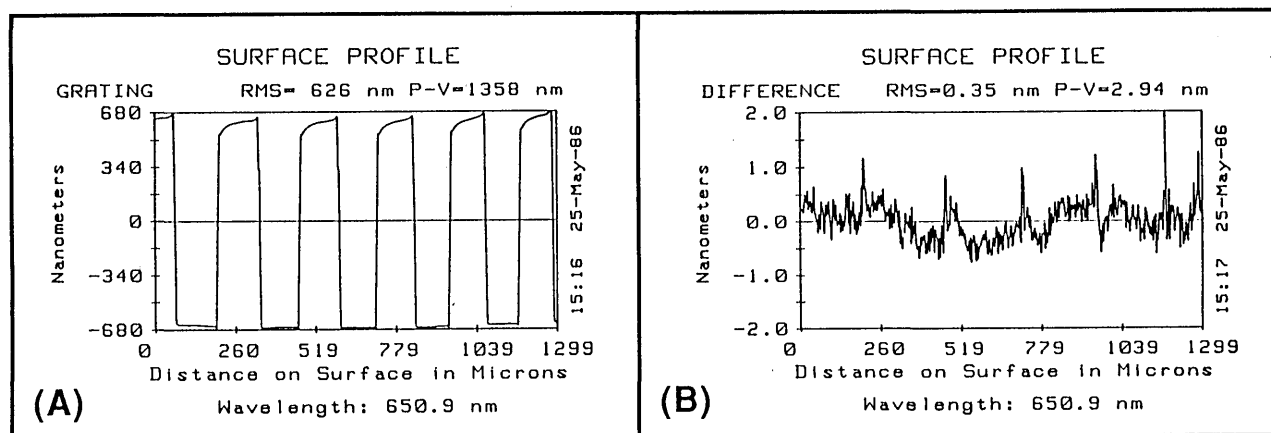


Fig. 10. (A) Corrected profile of grating at 650.9 nm showing correct step heights and less noise. (B) Repeatability of corrected profile of (A).

integrated two-wavelength phases to determine fringe orders. The measurement precision is  $\lambda/1000$  at the equivalent wavelength. Visible wavelength precision is attainable by using the equivalent wavelength measurement to determine the fringe orders for the single-wavelength data. With this technique, a dynamic range of  $10^4$  is possible for the measurement of step heights.

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