White-light interference microscopy: minimization of spurious diffraction effects by geometric phase-shifting

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Abstract: A common problem when profiling surfaces with steps or discontinuities using white-light (coherence-probe) interferometry is localized spikes (batwings) or spurious peaks due to diffraction effects. We show that errors due to these effects can be minimized by processing the irradiance data obtained with an achromatic phase-shifter operating on the geometric (Pancharatnam) phase to yield the values of the surface height.

OCIS codes: (180.3170) Interference microscopy; (180.1655) Optical coherence tomography; (180.6900) Three-dimensional microscopy; (100.3175) Interferometric imaging; (170.1650) Coherence imaging; (350, 1370) Berry phase; (100.6890) Three-dimensional image processing; (120.2830) Height measurements.

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1. Introduction

A problem with interferometric profilers using monochromatic light is 2π phase ambiguities which arise at steps.

One way to overcome this problem is by using white light and scanning the test surface in depth. This technique is known as low-coherence interference microscopy, or coherence-probe microscopy. If we assume that the test surface is moved along the height (z) axis in a series of steps, the irradiance at any point in the image, corresponding to a point on the object whose height is h, is

$$I(z) = I_1 + I_2 + 2(I_1 I_2)^{1/2} g(p) \cos\left[(2\pi/\bar{\lambda})p + \phi_0\right], \quad (1)$$

where I_1 and I_2 are the irradiances of the two beams acting independently, $g(p)$ is the fringe-visibility or coherence function (which corresponds to the envelope of the interference fringes), and $\cos[(2\pi/\bar{\lambda})p+\phi_0]$ is a cosinusoidal modulation. In Eq. (1), $\bar{\lambda}$ is the mean wavelength of the source, $p=2(z-h)$ is the difference in the lengths of the optical paths traversed by the two beams, and ϕ_0 is the phase difference due to the phase shifts on reflection at the beam splitter, the mirror and the test surface. The position along the height axis yielding maximum visibility of the fringes (the coherence peak) for each pixel in the image corresponds to the height of the object at that point and can be located by Fourier analysis of the irradiance data [1, 2], or by phase-shifting [3].

If the phase shifts are introduced by changing the optical path difference, they vary inversely with the wavelength. The resulting errors can be minimized by using a five-step algorithm [4] to calculate the fringe visibility, and a seven-step or eight-step algorithm [5-7] to calculate the fractional (wrapped) phase at each position along the height (z) axis. The height of the object can then be obtained by using the location of the coherence peak to identify the step nearest to zero optical path difference and combining this information with the value of the fractional (wrapped) phase.

2. Diffraction-induced artifacts

A troublesome effect noticed in coherence-probe microscopy is localized spikes ('batwings') at the edges of steps [8], or additional coherence peaks [9], due to diffraction. Batwings are particularly troublesome because they show up for every established white-light vertical-scanning technique [8]. They are noticeable at steps whose height is less than the coherence length of the light.

It appears that while the algorithms used in conventional phase-shifting interferometry are relatively insensitive to deviations of the phase shifts from their nominal value due to variations in the wavelength, problems can arise if the phase shifts are introduced (as for example, with a Mirau interference objective) by moving the objective, or the object, along the height axis. In this case, the position of the focal plane of the objective with respect to the object changes, and the irradiance values corresponding to different values of the phase shift are acquired in planes at different heights. As a result, they are affected to different degrees by diffraction at steps and discontinuities on the object. The magnitude of these effects depends on a number of factors, including the coherence length of the illumination and the height of the step, as well as the numerical aperture of the objective and the distance between the surface of the object and the focal plane of the objective [10].

We have found that errors due to diffraction effects can be reduced by using a phase-shifter operating on the geometric (Pancharatnam) phase [11, 12]. In this case, achromatic phase shifts can be introduced at each position of the object along the height axis without changing the position of the focal plane of the objective with respect to the object. Since all the irradiance values used finally to evaluate the height of each point on the object are acquired in a single selected plane, very close to the plane in which that point is located, errors in the values of the height, due to diffraction effects, are minimized.

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3. Optical system

Figure 1 is a schematic of the modified Linnik interference microscope that we have used for our measurements [13]. A tungsten-halogen lamp is used as the source, and the linearly polarized beam transmitted by the polarizer is divided at the polarizing beam-splitter into two orthogonally polarized beams, which are focused onto a reference mirror and the test surface by two identical infinity-tube-length microscope objectives. After reflection at the reference mirror and the test surface, these two beams return along their original paths to a second (nonpolarizing) beam-splitter, which sends them through an analyzer to a CCD array camera.

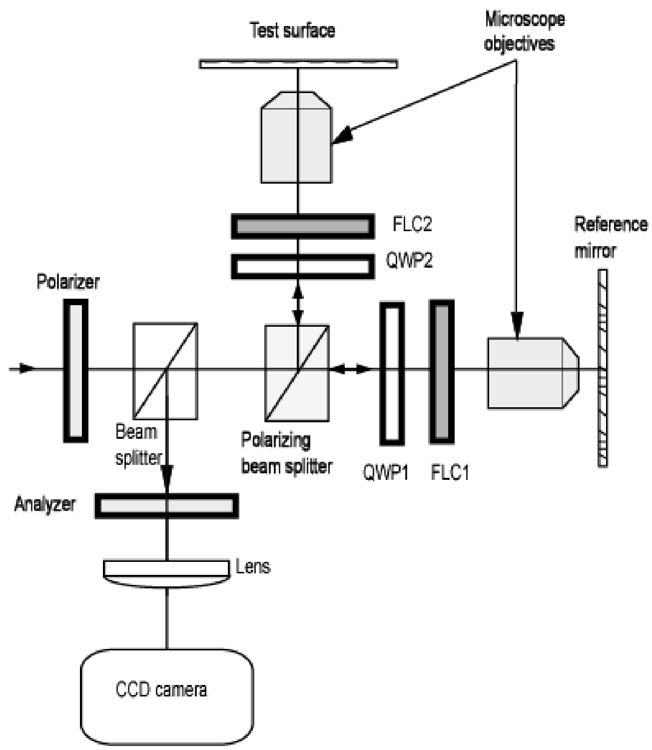

Fig. 1. Schematic of the optical system of the modified Linnik interference microscope using a pair of switchable achromatic phase-shifters.

The phase difference between the two beams is varied by a system operating on the geometric (Pancharatnam) phase featuring two identical switchable achromatic phase-shifters, one in each beam [14, 15], located between the beam splitter and the corresponding microscope objective. Each phase shifter consists of a quarter-wave plate (QWP), with its principal axis at 45° to the plane of polarization of the beam, followed by a ferro-electric liquid crystal device (FLC) with a retardation of a quarter wave. In this arrangement, if the principal axis of FLC1 is switched through an angle of 45°, the beam will experience an additional phase shift of 90°. The variation of this additional phase shift with the wavelength can be minimized by setting FLC1 so that its principal axis switches between angles of 22.5° and 67.5°. Similarly, if the principal axis of FLC2 is switched through an angle of 45°, the other beam experiences an additional phase shift of 90°, which is equivalent to the first beam experiencing a phase

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shift of -90°. With simple quarter-wave plates made of PVA (polyvinyl alcohol), the maximum deviations of the phase shift from its nominal value, over the range of wavelengths from 450 nm to 700 nm, are only ±6.7°, while the deviations of the output amplitude from its normalized maximum value of 1.00 are less than 0.015.

4. Experimental procedure

Measurements were made with a pair of 50× objectives with a NA of 0.8, using, as a test sample, a VLSI step-height standard (VLSI Standards, Inc.) with a step having a nominal height of 900 nm.

To make measurements, the test sample was moved along the height (*z*) axis, by means of a piezoelectric translator, in steps $\Delta z = 0.1 \mu m$ over a range of 4.0 μm centered approximately on the middle of the step-height. At each step, three measurements were made of the irradiance at each point in the fringe pattern, corresponding to additional phase shifts using the geometric phase shifter, of 0° and $\pm 90^\circ$.

The visibility of the interference fringes for each point on the object, at each step along the height (*z*) axis, was calculated from the three sets of irradiance measurements made at this setting with the geometric phase shifter, using the formula [15]

$$V = \frac{\left[\left(I_{90} - I_{-90} \right)^2 + 2\left(I_0 - I_{90} - I_{-90} \right)^2 \right]}{I_{90} + I_{-90}}. \quad (2)$$

An estimate of the surface height at each point was then obtained by fitting a curve to the visibility data for this point and finding the position of the peak of the visibility curve along the height (*z*) axis.

5. Experimental results

Figure 2 shows a 3-D plot of the surface of the test sample produced using the visibility data obtained with the modified Linnik microscope and the geometric phase shifter, while Fig. 3 shows a profile of the same test sample produced with a system using a conventional method of coherence sensing. As can be seen, the profile obtained with the conventional method of coherence sensing exhibits a localized spike (batwing) at the edge of the step, while the plot obtained with the geometric phase shifter is free from such spurious diffraction effects.

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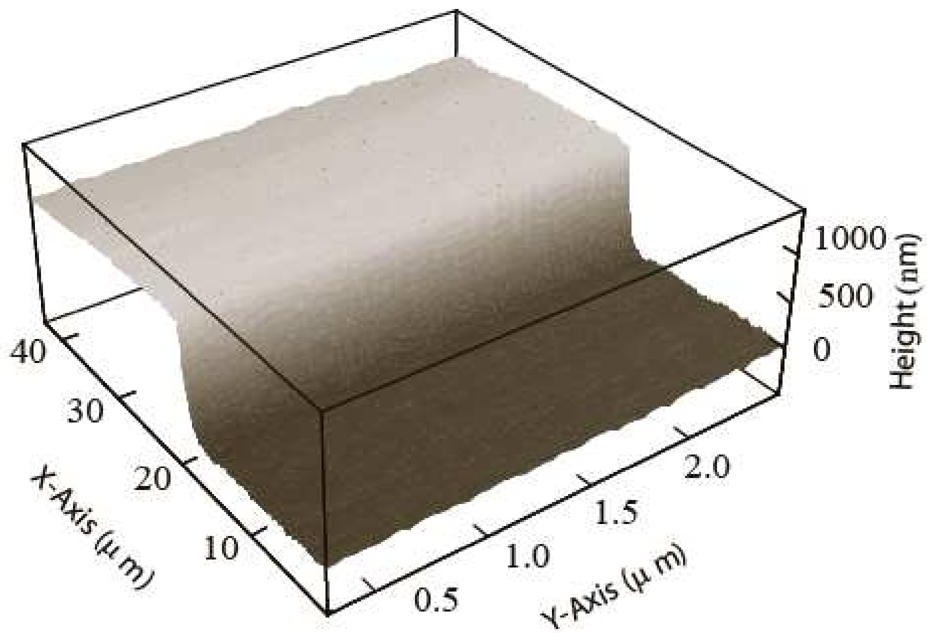

Fig. 2. 3-D plot of a section of the surface of the test sample produced using the visibility data obtained with the modified Linnik interference microscope and the geometric phase shifter.

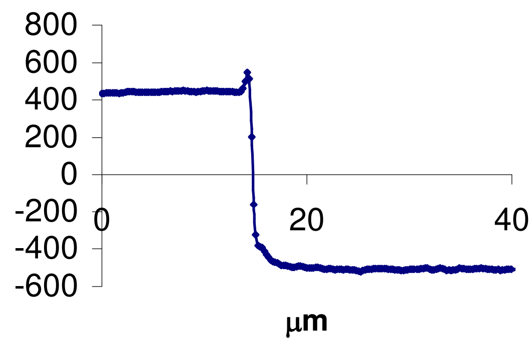

Fig. 3. Profile of the surface of the same test sample produced with a system using a conventional method of coherence sensing.

6. Conclusion

When profiling surfaces with steps using white-light (coherence-probe) interferometry, errors due to spurious diffraction effects can be minimized by processing, for each point on the object, the irradiance data obtained with an achromatic phase-shifter operating on the geometric (Pancharatnam) phase to obtain the height of the surface at that point.

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