Low-coherence interference microscopy with an improved switchable achromatic phase-shifter

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Abstract: We present results obtained with a computer-controlled low-coherence interference microscope featuring a modified optical layout that uses a pair of fast switchable achromatic phase-shifters. This layout makes it possible to use ferro-electric liquid-crystal devices made with readily available FLC materials having a switching angle of 45°, and obtain phase shifts of 0° and ±90°. The use of phase shifts of 0° and ±90° simplifies calculations of the fringe visibility and the fractional fringe-order and yields maximum accuracy.

OCIS codes: (180.3170) Interference microscopy; (110.4500) Optical coherence tomography; (180.6900) Three-dimensional microscopy; (120.3180) Interferometry; (170.1650) Coherence imaging; (110.6880) Three-dimensional image acquisition.

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1. Introduction

Low-coherence interference (LCI) microscopy overcomes the problem of ambiguities encountered in profiling micromachined surfaces exhibiting steps and discontinuities. In this technique, the object is scanned in height, using a broad-band source, and the degree of coherence (fringe visibility) between corresponding pixels in the images of the object and reference beams is measured. The location of the visibility peak along the scanning axis gives the height of the surface at that point [1, 2].

#8871 - $15.00 USD Received 22 September 2005; revised 25 October 2005; accepted 25 October 2005

Digital filtering techniques have been used to recover the fringe visibility curve and locate the visibility peak, but they require measurements with increments of the optical path that are less than a quarter of the shortest wavelength and are also numerically intensive. A more direct approach is based on phase shifting.

However, with a broad-band source, a problem with conventional techniques of phase shifting, as for example by moving a mirror to change the optical path difference, is that the phase shift introduced is inversely proportional to the wavelength. This problem can be avoided by using a phase shifter operating on the geometric (Pancharatnam) phase to obtain phase shifts that are independent of the wavelength [3].

2. Optical system

As shown in Fig. 1, our LCI microscope is based on a Linnik configuration. A tungsten-halogen lamp is used as the source. 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.

The phase difference between the two beams is varied by a system operating on the geometric (Pancharatnam) phase. One arrangement used earlier consisted of a quarter-wave plate and a rotating polarizer placed in the beams leaving the second beam splitter [4]. Rotation of the polarizer through an angle θ introduces an additional phase difference 2θ between the two beams. An alternative arrangement is a rotating half-wave plate between two quarter-wave plates (a QHQ phase-shifter) [3]. Rotation of the half-wave plate through an angle θ introduces an additional phase difference 4θ between the two beams. However, both these phase shifters have the drawback that the time required to rotate the polarizer, or the half-wave plate, from one setting to the next is much longer than the scan time of the CCD array camera.

#8871 - $15.00 USD Received 22 September 2005; revised 25 October 2005; accepted 25 October 2005

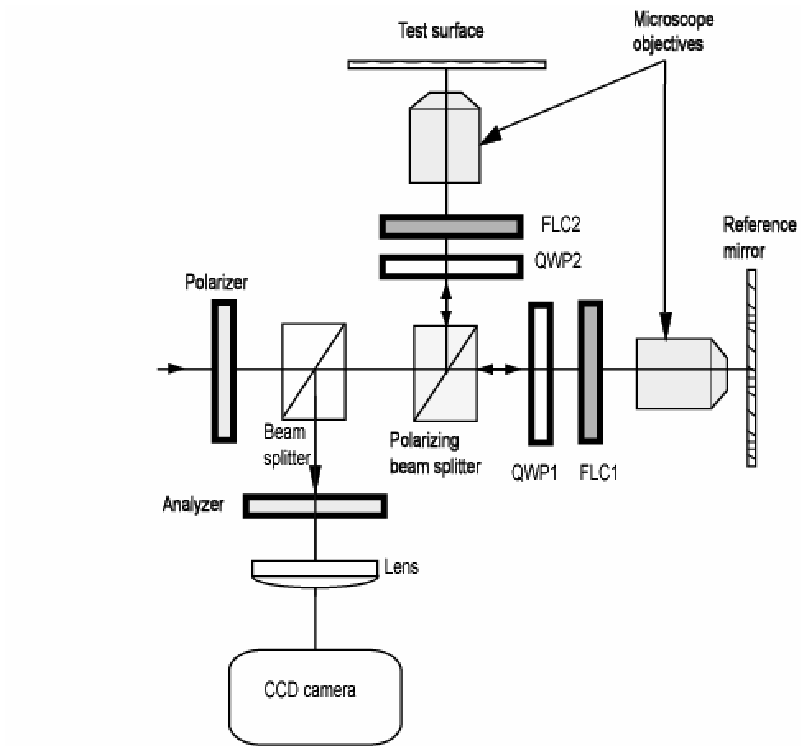

Fig. 1. Modified LCI microscope using two QWPs and two FLC devices.

2.1 Switchable phase-shifters

Data acquisition can be speeded up by replacing the half-wave plate in the QHQ phase-shifter by two ferro-electric liquid crystal (FLC) devices, which are equivalent to half-wave retarders whose principal axes can be switched through a known angle in a very short time [5, 6]. A problem with this system is that the materials used in commercially available FLC devices have switching angles of $\pm 45^0$ which would, in this case, result in phase shifts of $\pm 180^0$. One solution [6] has been to use custom-made FLC devices with a switching angle that differs significantly from 45^0. However, such FLC materials are not readily available.

We have overcome this problem with a modified design featuring FLC devices using commercially available materials with a switching angle of 45^0. The use of such materials opens the way to wide use of this technique.

2.2 Improved switchable phase-shifter

Since the basic optical scheme is that of a Michelson interferometer, we have used an alternative arrangement featuring two identical switchable phase-shifters, one in each beam [7], located, as shown in Fig. 1, between the beam splitter and the corresponding microscope objective. Each phase shifter consists of a quarter-wave plate (QWP), with its principal axis at 45^0 to the plane of polarization of the beam, followed by a ferro-electric liquid crystal cell (FLC) with a retardation of a quarter-wave and a switching angle of 45^0, with its principal axis set at an angle θ to that of the quarter-wave plate.

In this arrangement, the linearly polarized light leaving the beam splitter, in one of the

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arms of the interferometer, can be represented, as shown in Fig. 2, by the point A_1 on the equator of the Poincaré sphere. After traversing (say) QWP1, the light is circularly polarized and is represented by the point S. After passing through FLC1, it is again linearly polarized and represented by the point A_2 on the equator at an angular distance 2θ from A_1. The beam is then reflected back and retraces its path back through FLC1 and QWP1. As a result, the point representing the polarization state of the beam moves to N and then back to A_1.

Since the point representing the polarization state has traversed the closed circuit $A_1SA_2NA_1$ on the Poincaré sphere, the beam suffers a phase shift equal to half the solid angle subtended by the circuit $A_1SA_2NA_1$ at the center of the sphere, which is equal to 2θ. This phase change is a manifestation of the Pancharatnam phase [8]. If, now, the principal axis of F1 is switched through an angle of 45^0, the beam will experience an additional phase shift of 90^0. The variation of this additional phase shift with the wavelength can be minimized by setting F1 so that its principal axis switches between values of θ of 22.5^0 and 67.5^0 [7].

Similarly, if the principal axis of FLC2 is switched through an angle of 45^0, the other beam experiences an additional phase shift of 90^0, which is equivalent to the first beam experiencing a phase shift of -90^0.

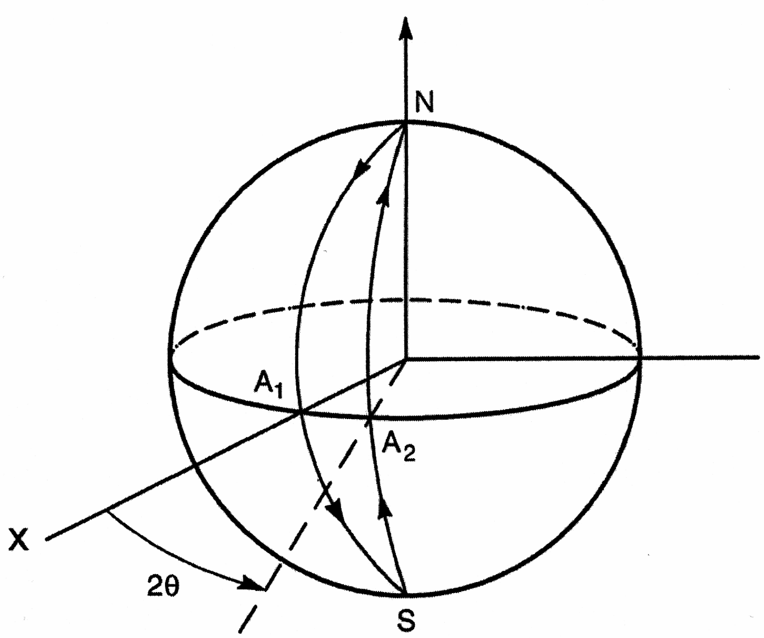

Fig. 2. Closed path followed by the polarization state on the Poincare sphere.

This system can be used to produce phase shifts of 0^0 and $\pm 90^0$ that are almost independent of the wavelength over the range of visible wavelengths. With simple quarter-wave plates made of PVA (polyvinyl alcohol) the maximum deviations of the phase shift over the range of wavelengths from 450 nm to 700 nm, from its value at the design wavelength of 550 nm, are only $\pm 6.7^0$. The corresponding deviations of the output amplitude from its

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normalized maximum value of 1.00 are less than 0.015.

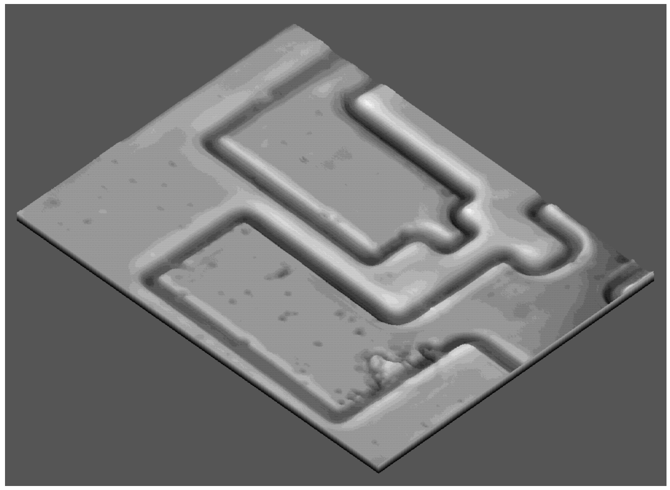

Fig. 3. Surface profile of an integrated circuit measured with our system. The lateral dimensions of the object are 25 μm x 43 μm, height 1 μm.

3. Experimental results

The sample (an integrated circuit) was moved along the height (z) axis, by means of a piezoelectric translator, in steps $\Delta z = 0.33\mu m$ over a range of $10\mu m$ centered approximately on the zero-order white-light fringe. At each step, three measurements were made of the intensity at each point in the fringe pattern, corresponding to no additional phase shift and additional phase shifts of 90^0 and -90^0. The corresponding values for the visibility of the interference fringes at each point, for each step, could then be calculated, from these three sets of intensity measurements, using the simple formula

$$V = \frac{\left[\left(I_{90} - I_{-90}\right)^2 + \left(I_0 - I_{90} - I_{-90}\right)^2\right]^{1/2}}{I_{90} + I_{-90}} \tag{1}$$

The surface height at each point was obtained by fitting a curve to the visibility data for each pixel and finding the position of the peak of the visibility curve along the scanning axis. The location of the visibility peak for each pixel along the scanning (height) axis gave the height of the surface at the corresponding point on it. More accurate values of the surface height can be obtained, where required, by processing the intensity data at the step nearest to the visibility peak to obtain the corresponding values of the phase [8], using the relation

$$\tan\phi = \frac{I_{90} - I_{-90}}{2I_0 - I_{90} - I_{-90}} \tag{2}$$

Since the switching time of the FLC materials used in the phase shifters was less than 50

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μs, acquisition of the intensity data at a 745×567 array of points over a range of heights of $10 \mu m$ at 30 height settings for 3 frames at each height settings including A/D conversion took only about 78 seconds. The intensity data were then processed to obtain the values of the surface height in about 15 seconds.

Figure 3 shows a three-dimensional representation of the surface of an integrated circuit (lateral dimensions, $23 \mu m \times 43 \mu m$, height $1 \mu m$) obtained with this system.

4. Conclusions

We present results obtained with a low-coherence interference microscope, based on a Linnik interferometer, incorporating a pair of fast switchable achromatic phase-shifters. This arrangement uses FLC devices made with readily available FLC materials having a switching angle of 45^0 and produces phase shifts of 0^0 and $\pm 90^0$. The use of phase shifts of 0^0 and $\pm 90^0$ simplifies calculations of the fringe visibility and the fractional fringe-order and yields maximum accuracy.

Received 22 September 2005; revised 25 October 2005; accepted 25 October 2005