Low-coherence interference microscopy using a ferro-electric liquid crystal phase-modulator

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Abstract: We describe a computer-controlled low-coherence interference microscope, based on a Linnik interferometer configuration that can rapidly and accurately map the shape of micro-machined surfaces exhibiting steps and discontinuities. The novel feature of the system is a fast, switchable achromatic phase-modulator operating on the geometric phase, using a pair of ferro-electric liquid crystal devices.

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.

References and links

1. M. Davidson, K. Kaufman, I. Mazor, and F. Cohen, "An application of interference microscopy to integrated circuit inspection and metrology," Integrated Circuit, Metrology, Inspection and Process Control, Proc. SPIE **775** (Bellingham, Washington: SPIE), 233-247 (1987).
2. D. Huang, E. A. Swanson, C. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M.R. Lee, T. Flotte, K. Gregory, C.A. Puliafito, and J.G. Fujimoto, "Optical coherence tomography," Science **254**, 1178-1181 (1991).
3. Lee, B. S. and Strand, T. C., "Profilometry with a coherence scanning microscope," Appl. Opt. **29**, 3784-3788 (1990).
4. P. Hariharan, K. G. Larkin and M.Roy, "The geometric phase: interferometric observations with white light," J. Mod. Opt. **41**, 663-667 (1994).
5. P. Hariharan and M.Roy, "White-light phase-steppping interferometry for surface profiling," J. Mod. Opt. **41**, 2197-2201(1994).
6. M. Roy, P. Svahn, L. Cherel, and C.J.R. Sheppard, "Geometric phase-shifting for low-coherence interference microscopy," Opt. and Lasers in Eng. **37**, 631-641 (2002).
7. M. O. Freeman, T. A. Brown and D. M. Walba, "Quantized complex ferroelectric liquid crystal spatial light modulators," Appl. Opt. **31**, 3917-3929 (1992).
8. G. D. Love, and R. Bhandari, "Optical properties of a QHQ ferroelectric liquid crystal phase modulator," Opt. Comm. **110**, 475-478 (1994).
9. P. Hariharan, and P. E. Ciddor, "Achromatic phase-shifters:2. A quantized ferroelectric liquid-crystal system," Opt. Comm. **117**, 13-15 (1995).
10. P. Hariharan, "Fast, common-path switchable, achromatic phase-shifter for polarization interferometry," J. Mod. Opt. **44**, 857-861 (1997).
11. P. Hariharan and P. E. Ciddor, "Improved switchable achromatic phase shifters," Opt. Eng. **38**, 1078-1080 (1999).
12. P. Hariharan and M. Roy, "White-light phase-stepping interferometry: measurement of the fractional interference order," J. Mod. Opt. **42**, 2357-2360 (1995).

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1. Introduction

Two new techniques based on low-coherence interferometry (LCI) have been developed recently. One is coherence probe microscopy, which is used for surface inspection and profiling, particularly in the semiconductor device industry [1]. The other is optical coherence tomography, which is used for medical diagnostics, particularly in ophthalmology and dermatology [2]. In both these techniques, coherence gating is used for optical sectioning.

The optical sectioning property of LCI is due to the short coherence length of the illumination. Since the interference term is appreciable only over a short range of depths, an optical section is extracted. In coherence-probe microscopy, three-dimensional images are produced by scanning the object in height and evaluating the degree of coherence (fringe visibility) between corresponding pixels in the images of the object and reference planes. Digital filtering techniques have been commonly used to recover the fringe visibility curve and locate the visibility peak [3], 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. An alternative method is based on phase shifting. With laser illumination, phase shifting is traditionally performed by moving a mirror to change the optical path difference. However, with a broad-band source, a problem is that the phase shifts of the different spectral components are not the same. This problem has been overcome by geometric phase modulation using polarization optics to obtain an achromatic phase shift [4, 5, and 6].

We have developed a computer-controlled low-coherence interferometric microscope based on a Linnik interferometer configuration which can rapidly and accurately map the shape of micro-machined surfaces exhibiting steps and discontinuities. The novel feature of this instrument is the use of a geometric phase modulator (GPM) featuring a pair of ferro-electric liquid crystal (FLC) devices to evaluate the fringe visibility and the fractional interference order directly for each point on the object.

2. FLC geometric phase modulator (GPM)

A conventional GPM consists of a half-wave plate (HWP), sandwiched between two quarter-wave plates (QWP1 and QWP2) and two polarizers. The two quarter-wave plates have their optic axes fixed at an angle of 45° to the plane of polarization of the incident linearly polarized beam, while the HWP can be rotated by known amounts. When the HWP is rotated through an angle θ, the linearly polarized output beam acquires a geometric phase shift equal to 2θ. This phase shift is very nearly independent of the wavelength.

However, such a GPM has the drawback that the time required to rotate the HWP from one angle to another is much longer than the time required to acquire the values of intensity at an array of points in the interference pattern with a CCD camera. This problem can be overcome by using retarding plates based on ferro-electric liquid crystal devices, whose principal axes can be switched through a known angle in a very short time [7].

Designs for a GPM using a FLC cell have been proposed by various authors [8, 9]. A schematic of an achromatic phase shifter using two FLC devices is shown in Fig. 1. With a single linearly polarized beam, it is possible to use conventional FLC cells, which have a switching angle of 45°, and obtain phase shifts of ±90°.

However, in our optical setup, the entrance polarizer P1 is followed by a polarizing beam splitter, and we have two orthogonally polarized beams incident on the first QWP. One beam then acquires a phase shift equal to 2θ, while the other beam acquires a phase shift equal to -2θ. The additional phase difference introduced between the two beams is therefore 4θ, and a switching angle of 45° would result in phase shifts of ±180° between the two beams, which would not be useful. This problem can be solved by using FLC devices with a switching angle that differs significantly from 45° [10]. We have used two custom made FLC cells with

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switching angles of 51°, which produce switchable phase shifts of ±204°. These FLC cells were made by Displaytech, Inc., USA using a ferroelectric liquid crystal mixture (Felix 015-100) supplied by Hoechst AG, Germany and were optimized for 550 nm (±50nm).

With a proper choice of initial settings, the deviations of the actual phase shifts from their nominal values can be held to less than ±15° over the range of wavelengths from 490 nm to 650 nm [11].

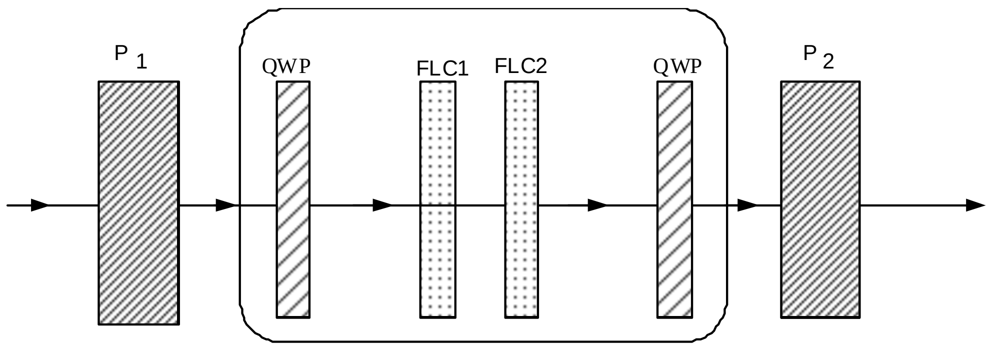

Fig.1. GPM with FLC devices. Two FLC devices are sandwiched between two quarter-wave plates.

3. Experiments and results

A schematic diagram of the low-coherence interference microscope is presented in Fig. 2. A tungsten halogen lamp (12 V, 100W) is used as a source. A 3mW He-Ne laser is also provided for finding the interference fringes. 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 40X microscope objectives with a numerical aperture of 0.75. After reflection at the reference mirror and the test surface, these beams return along their original paths to a second beam splitter, which sends them through a second polarizer to the CCD array camera.

The phase difference between the beams was varied by a GPM, similar to that shown in Fig. 1, consisting of two QWPs with their axes fixed at an azimuth of 45°, and a pair of FLCs whose axes could be switched by applying appropriate voltages. As mentioned earlier, the entrance polarizer P1 is placed ahead of the polarizing beam splitter, so that two orthogonally polarized beams emerge from the interferometer; the analyzer (output polarizer) P2 then produces interference.

To illuminate the object uniformly, a Koehler illumination system was used, consisting of lenses L1-L4 together with a microscope objective. This system allows separate control of both the illumination aperture stop and the field stop. Stopping down the illumination aperture allows the system to be operated as a conventional interference microscope. The sample was moved along the *z* axis by means of a piezoelectric translator (PZT) in steps $\Delta z = 0.33\ \mu m$ over a range of 14 μm 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 phase shift and additional phase shifts of ±204° produced by the FLC phase modulator. The surface height was obtained by finding for each pixel, in the first instance, the position of the peak of the visibility curve along the scanning axis. Accurate values of the fractional interference order could then be obtained from the corresponding phase data [12].

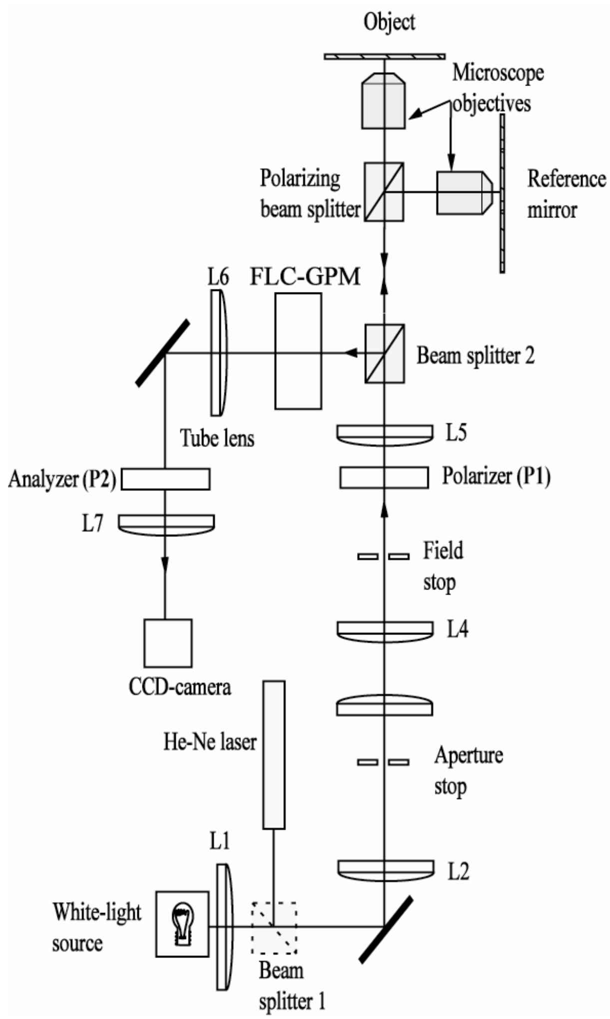

Fig. 2. Schematic of the low coherence interference microscope using an FLC phase modulator.

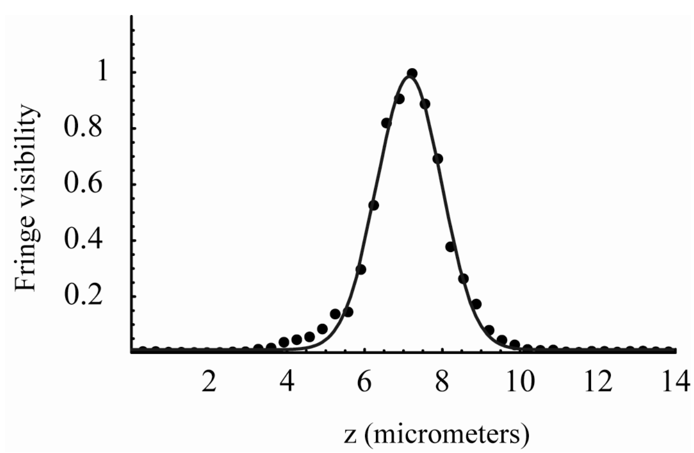

Fig. 3. Visibility of the interference fringes as a function of the position of the sample along the z axis.

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Figure 3 shows a typical curve obtained for the visibility of the interference fringes at the center of the field as a function of the position of the sample along the z axis. The solid curve represents the best-fit Gaussian. The value of z corresponding to the peak visibility of the interference fringes could be obtained from this curve fit to within a few nanometers. Figure 4 shows the surface profile of an integrated circuit obtained with the FLC phase modulator in our LCI microscope.

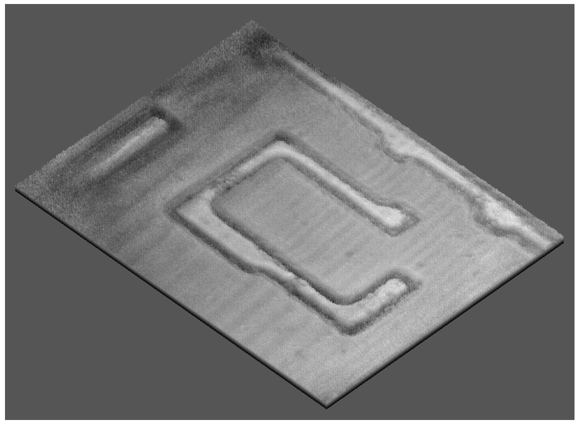

Fig. 4. Surface profile of an integrated circuit measured with our system. The lateral dimensions of the object are 25 μm x 43 μm, height 1 μm.

4. Conclusions

We have demonstrated the successful use of a GPM using FLC cells for low-coherence interferometric surface profiling on a microscopic scale. The range of surface heights that can be profiled with this technique is limited only by the characteristics of the PZT used to translate the test specimen along the *z* axis and the available computer memory. However, since the steps between height settings at which data have to be taken can correspond to changes in the optical path difference greater than a wavelength, a much smaller number of steps are required to cover the same range of depths; in addition, calculations of the visibility at each step are quite simple and quick. Other advantages of using a ferro-electric GPM are its very short response time (< 100 μs) and its freedom from vibration, because it has no mechanical moving parts.

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