# Liquid-crystal point-diffraction interferometer

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A new point-diffraction interferometer has been developed with a liquid-crystal filter that permits arbitrary phase shifts to be introduced between the object and reference beams. A microsphere embedded within the liquid-crystal layer provides a locally generated reference beam. We phase shift the object beam by varying a voltage across the liquid crystals, thereby altering the refractive index of the birefringent nematic liquid crystals.

The point-diffraction interferometer[1,2] has long been used as a robust instrument for the measurement of optical wave fronts for lens testing and fluid-flow diagnostics. Its usefulness is limited primarily to qualitative interferogram analysis because its common path design precludes easy implementation of phase-shifting interferometry. The instrument is robust precisely because of this common path design, but the same feature makes it difficult to shift the phase of one beam relative to the other so as to employ phase-shifting techniques. A variation of the point-diffraction interferometer developed by Kwon[3] uses a specially fabricated diffraction grating to produce three phase-shifted interferograms simultaneously. The wave-front phase can be determined from these interferograms; however, three area detectors are required.

We describe a new point-diffraction interferometer with a liquid-crystal filter that permits arbitrary phase shifts to be introduced between the object and reference beams. A microsphere embedded within the liquid-crystal layer provides a locally generated reference beam. The object beam is phase shifted by modulation of the voltage across the liquid crystals, thereby altering the refractive index of the birefringent nematic liquid crystals.

The liquid-crystal point-diffraction interferometer (LCPDI) consists of dyed parallel nematic liquid crystals sandwiched between two glass plates (Fig. 1). Miniature cylindrical rods are placed at the edges to serve as spacers. A transparent deformable microsphere slightly larger than the cross section of the rods is placed between the glass plates, replacing a small volume of liquid crystal. Coherent light is brought to nearly a focus on the microsphere. The beam width is several times larger than the microsphere, so some of the beam travels through the liquid crystals, forming the object beam. The rest is diffracted by the microsphere and forms the reference beam.

The glass plates have transparent electrodes deposited on their inner surfaces. Leads are soldered onto the electrodes so that an alternating current can be applied across the liquid crystal. The applied field reorients the liquid-crystal molecules and changes the refractive index of the uniaxial liquid-crystal layer.[4] The amount of change is determined by the amplitude of the ac voltage. We can thus alter the phase of the object beam without affecting the reference beam.

Dye is added to the liquid crystals to attenuate the object beam to roughly the same intensity as the reference beam. This improves the fringe contrast, but the dye molecules rotate with the liquid-crystal molecules, causing an unwanted intensity modulation when the phase is shifted.

The LCPDI is used as follows: Spatially filtered light from an argon-ion laser is collimated and passed through a linear polarizer. A 100-mm lens nearly focuses the $f/6$ beam onto the liquid-crystal device. A second polarizer aligned parallel to the first removes depolarized light scattered off of the liquid-crystal molecules. Finally, a ground-glass viewing screen reveals the interferogram, which is recorded by a solid-state camera and stored on a computer. The shape of the interference fringes is determined by shape of the wave front incident upon the LCPDI and thus can be used to determine the quality of the

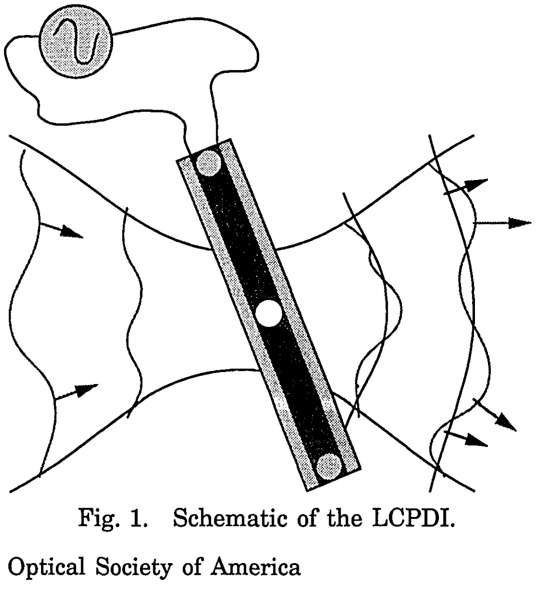

Fig. 1. Schematic of the LCPDI.

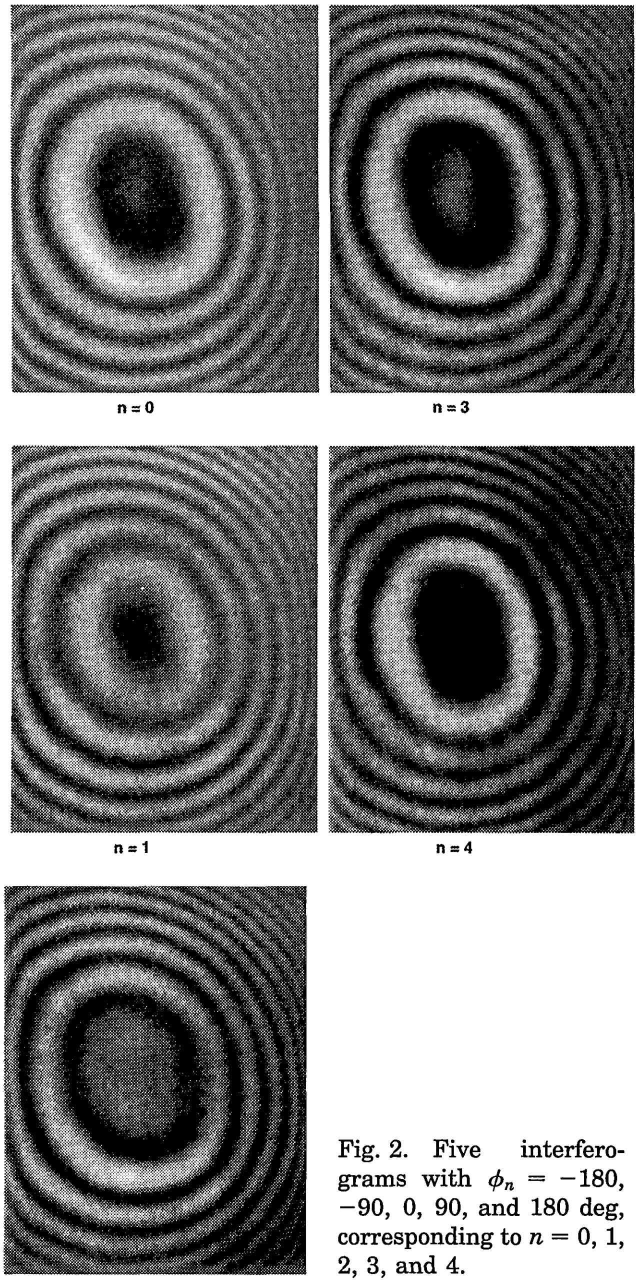

Fig. 2. Five interferograms with $\phi_n = -180$, $-90$, 0, 90, and 180 deg, corresponding to $n = 0$, 1, 2, 3, and 4.

ensemble of optical elements through which the beam passes. The LCPDI is tilted about the horizontal axis to minimize secondary fringes caused by multiple reflections from the glass plates. The LCPDI itself introduces aberrations that must be subtracted from the measured wave front. This correction will occur automatically, if the device is used to measure an initial wave front subtracted from an altered wave front, such as is the case in fluid studies.

A sequence of five interferograms made from the LCPDI is shown in Fig. 2. The interference patterns clearly show defocus fringes phase stepped by nominally 90°. Elliptical rather than circular patterns exist because the LCPDI is tilted. Each of these images has been normalized by a Gaussian function that approximates the object beam intensity distribution. We obtained this distribution by translating the LCPDI perpendicular to the optic axis, permitting the object beam to pass through without interference from the microsphere. The intensity distribution was then recorded for each phase step. The relative normalization factor at the pattern center for each frame is {0.39, 0.53, 0.59, 0.72, 1.00}.

Phase shifts generated by the LCPDI are not constant across the image because the shifting is done on a converging beam. If a voltage is applied such that the axial ray is shifted by $\beta$, then the portion of the wave front recorded at pixel $(x, y)$ will see a phase shift of $\beta + \epsilon$. The systematic error in the phase shift, $\epsilon$, is given by

$$\epsilon(x, y) = \frac{2\pi}{\lambda}[L(x, y) - t]\Delta n_{\mathrm{LC}}, \tag{1}$$

where $\Delta n_{\mathrm{LC}}$ is the change in the liquid crystal's refractive index as the voltage is stepped, $L$ is the physical path length through the liquid-crystal layer, $t$ is the thickness of the liquid-crystal layer, and $\lambda$ is the wavelength of the light.

Since there is an inherent error in the phase steps the Hariharan algorithm[5] is useful for minimizing the final measurement error. This algorithm requires five interferograms with the relative phase stepped in the following sequence:

$$\phi_n(x, y) = (n - 2)\beta + \varepsilon(x, y), \qquad n = 0, 1, 2, 3, 4. \tag{2}$$

Each interferogram then represents an equation of the form

$$I_n(x, y) = I0_n(x, y) \times \{1 + \eta_n(x, y)\cos[\theta(x, y) + \phi_n(x, y)]\}, \tag{3}$$

where $I0_n(x, y)$ represents the average intensity of the $n$th frame at pixel $(x, y)$, $\eta$ is the fringe contrast, and $\theta$ is the wave-front phase being measured. Standard phase-extraction algorithms such as the Hariharan algorithm assume that the average intensity and the fringe contrast remain constant from frame to frame so that a closed-form solution for the wave front phase exists. This assumption is not true for the LCPDI because neither the average intensity nor the contrast is constant as a result of dye-induced object beam intensity variations. However, we can easily determine the variation of the object beam intensity across the image from frame to frame by passing the focused beam through the liquid-crystal device far from the microsphere and imaging the transmitted light. This information can be used to normalize the interferograms, thus decreasing the intensity variations from frame to frame so as to reduce the phase measurement error.

In conclusion, a new point-diffraction interferometer has been developed that permits arbitrary phase shifts between the object and reference beams. The result is a robust interferometer that can employ phase-stepping interferometry for quantitative data reduction. Expected applications for this device include optical shop testing and flow diagnostics.

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