LAMP/91/1

INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS

LAMP SERIES REPORT

(Laser, Atomic and Molecular Physics)

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1991 MIRAMARE - TRIESTE

INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

Preface

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REAL TIME REFRACTIVE INDEX MEASUREMENT BY ESPI

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ABSTRACT

In this paper a method to measure refractive index variations in real time is reported. A technique to introduce reference fringes in real time is discussed. Both the theoretical and experimental results are presented and an example with phase shifting is given.

MIRAMARE – TRIESTE

March 1991

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INTRODUCTION:

Instantaneous full field information of changes in transparent media can find applications in fluid flow measurement, heat transfer, plasma diagnosis and aerodynamics to name a few. This has been usually accomplished by interferometry, holography, Moiré deflectometry and speckle methods. Speckle methods are particularly suitable for this purpose as they simply rely on the measurement of changes in the correlation of two speckle patterns [1,2]. The fringes obtained in speckle techniques are related to the movement of the speckle in between the exposures. Depending on the geometry of the optics used, they can be in–plane sensitive or out–of–plane sensitive. Comparisons in speckle interferometry have been accomplished in different ways. However, when the speckle patterns are processed electronically [3–6] (Electronic Speckle Pattern Interferometry, ESPI), repetitive and real time measurements can be carried out with relative ease. Also, the advantages offered by photographic speckle methods such as experimental stability and flexibility are also applicable to ESPI. This instantaneous processing in ESPI is achievable at the expenses of drastically lowered spatial resolution. Recently speckle techniques have been applied for the measurements of temperature variations in transparent media [7]. On the other hand, as ESPI offers many advantages such as real time processing and fringe analysis, it therefore might prove worthwhile to develop a full field density measurement technique.

In this paper we propose a novel method for the measurement of refractive index variations of a medium that relies on the principles of ESPI. The experimental configuration is a dual beam interferometry, where the path length in one of the beams is altered by varying the refractive index of the medium. The technique is of interferometric sensitivity and provides information about the change in the refractive index of the medium itself and not its gradient. However, in this arrangement as the first exposure is subtracted from the second, the method is independent of the type of probing waves (which can either be plane, spherical or even complicated) employed. Therefore, aberrations and scattering due to the optical elements have no influence on the fringes obtained. The phase errors due to the test windows are also eliminated as only the path length change between the exposures is displayed. The high speed of frame storage (at a frame rate of 1/30 sec) provides the possibility of avoiding the vibrational motion that can occur during exposures. Since the first exposure is stored and subtracted continuously by the incoming data, this real time operation can find applications in

industrial environment. Two methods with infinite and finite (reference) fringes are demonstrated. The finite fringe method is useful as it can remove the phase ambiguity encountered in the infinite fringe method. It has been recently demonstrated that a dual beam interferometric arrangement can also be employed for 3D contouring [8].

EXPERIMENTAL ARRANGEMENT:

The experimental configuration of the modified dual beam interferometric arrangement in ESPI is depicted in fig.1. The laser light is split into two beams 1 and 2, that illuminate a plane diffuse scatterer (ground glass) at an included angle θ. Both the beams 1 and 2, are expanded by means of a spatial filtering setup SF and collimated with the aid of lenses L_1 and L_2. The resulting interference speckle patterns, transmitted as scattered light from the ground glass, are collected by a TV camera and then processed with the help of a host computer. An experimental arrangement with a plane reflection scatterer can also be implemented, but it suffers from a disadvantage that higher laser power is required in order to raise the intensity of the scattered light. The first exposure is made without the phase object in position and then it is introduced in one of the arms of the interferometer in the second exposure. The two stored exposures are subtracted in real time and displayed on a TV monitor.

THEORY:

If A_1 and A_2 are the complex amplitudes of the waves due to the illuminating beams 1 and 2 respectively, then the first intensity record can be written as

$$I_1 = A_1 + A_2 + 2 A_1 A_2 \cos[\phi(x,y)] \quad (1)$$

where ϕ (x,y) is the phase of the speckle pattern. The third term is the cross interference term between both beams that carries the phase information. The phase object is introduced and the second intensity record can be written as

$$I_2 = A_1 + A_2 + 2 A_1 A_2 \cos[\phi(x,y) + \Delta] \quad (2)$$

where Δ is the phase change due to the phase object. The resulting fringes are obtained by subtracting the two intensity records with the help of a host computer. The modulus of the difference is taken and displayed as

$$|I_1 - I_2| = |\ 4 A_1 A_2 \sin(\phi + \Delta/2) \sin(\Delta/2)\ | \quad (3)$$

The output of the camera will have voltages proportional to the intensities i.e., $V_1 \propto I_1$ and $V_2 \propto I_2$. The difference between the voltages is displayed on the TV monitor. Thus the fringes depicting the phase change introduced due to the phase object is obtained. It is well known that the intensity of the two illuminating beams of a dual beam interferometer in ESPI have to be equal to yield high contrast fringes [6]. In our arrangement the speckles generated from beam 2 is of lower intensity as the camera is along the direction of beam 1. Thus the interfering speckles at the image plane of the camera are of low contrast. The contrast is enhanced by adjusting the intensity of the speckles generated by beam 2 to have the same intensity as that of the speckles generated from beam 1.

a: Infinite fringe

We derive in this section a generalized equation for the fringe formation. We assume that the diffuser is illuminated with two beams at angles θ_1 and θ_2. The schematic of the illumination and the observation geometry is shown in fig.2. Let the unit vectors of the illuminating beams 1 and 2 be $\hat{k}_1$ and $\hat{k}_2$ respectively and let $\hat{k}_3$ be the unit vector along the observation direction. The phase for the first exposure can be expressed as

$$\Delta_1 = (\hat{k}_1 - \hat{k}_2).\vec{L} \quad (4)$$

where $\vec{L}$ is a vector defined as $x\hat{i} + y\hat{j} + z\hat{k}$, where (x,y,z) are coordinate points on the diffuser plane. For the second exposure the phase in one arm of the beam is changed by introducing a phase object. The phase for the second exposure can be expressed as

$$\Delta_2 = (\hat{k}_1' - \hat{k}_2)\cdot\vec{L} \quad (5)$$

where $\hat{k}_1'$ is the change in the unit vector due to the phase object. In ESPI the first and the second exposure are subtracted pixel by pixel and the resultant difference is displayed on a monitor. However, this subtraction can be carried out in real time by storing the first exposure and subtracting the incoming second exposure at a TV frame rate. As the speed of the TV frame store is in the order of few tens of milliseconds,

vibrational motion that can occur in the first and second exposure are eliminated. Therefore, slow flow of gases and transparent liquids can also be visualized in real time. The phase change that is displayed on the TV monitor can be written down as

$$\Delta = \Delta_1 - \Delta_2 = (\hat{k}_1 - \hat{k}_1')\cdot\vec{L} \quad (6)$$

We assume that the phase change is only along the Z axis. From equation 6 it is clear that only the phase difference is displayed. So the technique is independent of the wave front employed in the two arms of the interferometer for probing the phase object. This also naturally eliminates the aberrations and scattering due to the optical elements in the setup and the phase errors of the test window. Substituting the unit vectors for a smooth varying refractive index, the final equation in the case of refractionless limit becomes

$$\Delta = \int [n_2(x,y,z) - n_1] \cos(\theta_1)\, dz = n\lambda \quad (7)$$

In our experimental arrangement, as shown in fig.1, θ_1 is zero as beam 1 lies parallel to the normal of the diffuser and eqn.(7) reduces to a simple form as

$$\Delta = \int [n_2(x,y,z) - n_1]\, dz = n\lambda \quad (8)$$

In this configuration we measure only out–of–plane variations of the refractive index. The method, in addition to the advantages gained as in hologram interferometry, is simple in arrangement, stable and operated in real time. However, it is limited by the factor that the maximum number of fringes that can be processed is dependant on the speckle size, which in fact is set by the pixel size of the TV camera. This method can be thought of as an equivalent to that of hologram interferometry. The only difference is that instead of a photographic medium for storing the different states of the object or transparent medium, a diffuser is used at this plane that helps to store the phase information in the speckles.

b: Finite/reference fringes

It is well known that in the infinite fringe method, ambiguity in the sign of of the phases is encountered. In this section we introduce a simple method to introduce reference fringes that helps in avoiding such problems. The initial phase for the first exposure can be written as

$$\Delta_1 = (\hat{k}_1 - \hat{k}_2).\vec{L} \qquad (9)$$

Before the second exposure the diffuser is tilted or rotated depending on the choice of the orientation of the reference fringes. The phase object is introduced and the final phase for the second exposure can be expressed as

$$\Delta_2 = (\hat{k}_1' - \hat{k}_2)\cdot\vec{L}' \qquad (10)$$

where $\vec{L}'$ is the new displaced vector due to the diffuser motion and is $(x+\delta x)\hat{i} + (y+\delta y)\hat{j} + (z+\delta z)\hat{k}$. The equation for fringe formation can be expressed as

$$\Delta = \Delta_1 - \Delta_2 = (\hat{k}_1 - \hat{k}_1')\cdot\vec{L} - (\hat{k}_1 - \hat{k}_2).(\vec{L} - \vec{L}') - (\hat{k}_1 - \hat{k}_1')\cdot(\vec{L} - \vec{L}') \qquad (11)$$

The first term carries the information about the phase object and the second is the reference fringes. The third term is very small and can be neglected. Substituting for $\hat{k}_1$, $\hat{k}_1'$, $\vec{L}$, $\hat{k}_2$ and $\vec{L}'$ eqn.(11) can be reduced to a simple form as

$$\Delta = \int [n_2(x,y,z) - n_1]\, dz - \sin(\theta_2)\, [y\varphi_t^2/2 + x\varphi_r] = n\lambda \qquad (12)$$

here φ_t and φ_r are the tilt and the rotation angles introduced around the Y and X axis respectively. Both the angles are assumed to be positive and are expressed in radians. The fringes for such as a geometry of illumination as shown in fig.2, lie parallel to the X axis for tilt and perpendicular the X axis for rotation. It is clear from the above equation that the tilt of the diffuser is less sensitive than the rotation.

EXPERIMENTAL RESULTS:

A 15 mW He–Ne laser was used for our experiments. The mirror in arm 2 of the interferometer was attached to a piezo electric translator in order to introduce phase shifts. A CCD camera with a Nikon objective was set to F/10 by an external aperture. The speckle patterns were digitized on a EPSON host computer and then displayed on a

TV monitor. The first experiment was carried out with a cigarette lighter as a source to change the refractive index of the medium. The lighter was placed in a stand with its nozzle just under the laser beam in arm 1. Fig.3a and Fig.3b shows the fringes for infinite and finite fringes with the gas on from the cigarette lighter. The photographs were directly taken from the TV monitor. Fig.4a shows the photograph for the same lighter with only gas on and fig.4b is with flames. This photographs were taken with a reflection scattering diffuser in place of the ground glass. The camera was placed in the opposite side and in between the two beams to image the diffuser. In this case the angle θ_1 has to be included as shown in eqn.(7). In the transmission mode the flame from the lighter illuminates the ground glass and makes viewing of fringes difficult. Therefore, the experiment was conducted in the reflection scattering mode and better results were obtained as the light did not directly fall on the photo sensor of the CCD camera.

To extract quantitative information from the interferograms the phase in one arm of the interferometer was shifted and three interferograms were recorded. The phase maps are calculated from the phase shifted data. The phase ambiguity was removed by comparing the phase difference between the adjacent pixel. A median window is introduced in the integration process to smoothen the data points. However it was found that the decorrelation that arises due to the change in the effective rays collected by the imaging system, is minimized as only phase shifts occur and not the movement of the speckles. Therefore fringes of good visibility were obtained in this arrangement. A single 5×5 median window was introduced to smoothen the speckle data and consistent results were obtained. As an example, a glass plate with a wedge of 2° and its surface not flat was considered for a test object. Three phase shifted interferograms were recorded shifted by phases of 90^0 each. The phase calculated at each point in the interferogram is

$$\Delta = \arctan\left[\frac{I_3 - I_1}{I_3 + I_1 - 2I_2}\right] \qquad (13)$$

Where I_1, I_2 and I_3 are the phase shifted intensities. Fig.5a shows the photograph of the fringes for such a glass plate and b,c and d are the phase data, 3D plot and the fringes generated from the phase data respectively.

CONCLUSIONS:

A method has been presented to measure refractive index changes. This provides a versatile tool for full field density studies in real time. The arrangement consists of a dual beam speckle interferometer coupled to a TV camera, whose information is fed into a host computer for processing the speckle patterns and displaying the fringes. The sensitivity is comparable to that in holographic interferometry, which represents an attractive advantage in terms of its potential industrial applications, besides being compact and easy to implement. It should be mentioned that the angle between the two beams is kept relatively small to obtain an uniform illumination at the image plane of the camera.

Parallel and straight reference fringes are obtained either by rotation or tilt of the diffuser. However, reference fringes of other forms can also be obtained by shifting the collimating lens. As an example, by slightly defocusing the collimating lens, fringes of circular symmetry are produced. This property of the setup has also been applied to test optical elements and the work in this direction is in progress.

Vibrations resulting from the motion of the optical components and air turbulences during exposures need to be eliminated for quantitative evaluations. Pulse laser is conventionally used to completely avoid motions in speckle and holographic techniques. In the case of ESPI a limit is set by the rate of frame store which is 1/30 sec. As this technique is a real time one, vibration effects that occur between exposures can be minimized.

ACKNOWLEDGEMENTS:

We wish to acknowledge the financial support of the Alexander von Humboldt Foundation. One of us (R.T.) would like to thank the help from the CONICET of Argentina. We wish to also thank Prof.H.J.Tiziani for the helpful discussions.

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FIGURE CAPTIONS:

Fig.1. Experimental arrangement for refractive index variation measurement. A Laser beam is split into two by a beam splitter and collimated after spatial filtering. The phase object is introduced in arm one of the interferometer.

Fig.2. Schematic geometry showing the parameters for the theoretical calculations.

Fig.3. Experimental results corresponding to the gas output from a cigarette lighter when the arrangement was set to a) infinite fringes mode and b) finite fringes mode. The finite fringes were obtained by rotating the diffuser through 0.5 mrad. The angle subtended by beam 1 and beam 2 i.e., θ_2 was 10°.

Fig.4. Same as fig.3 but with a reflection scatterer in place of the ground glass for a) the lighter with only gas on b) the same lighter with flame.

Fig.5. Experimental results with phase shifting for an optical glass plate with a wedge. a) fringes for the plate in the infinite fringe arrangement, b) phase data, c) 3D plot and d) computer plot of the fringes from the phase data.

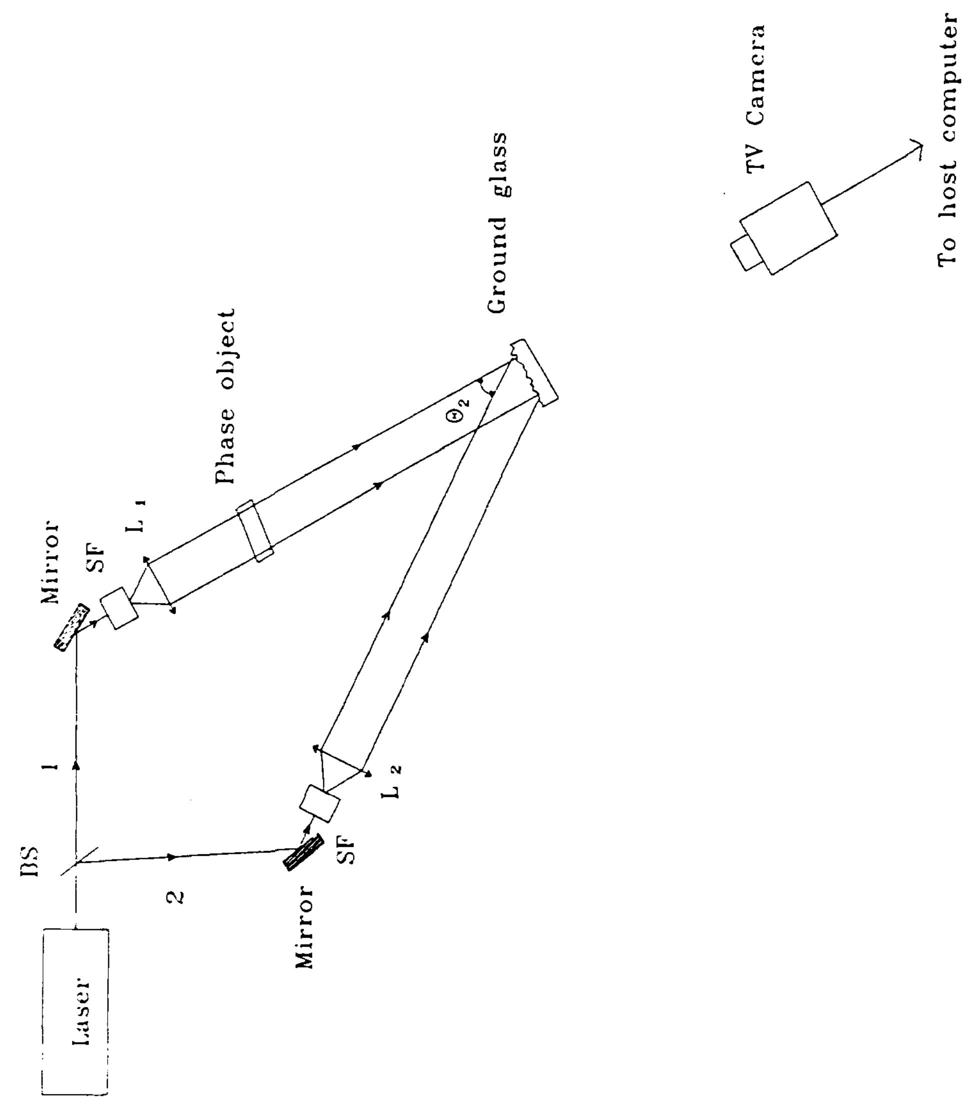


Fig.1

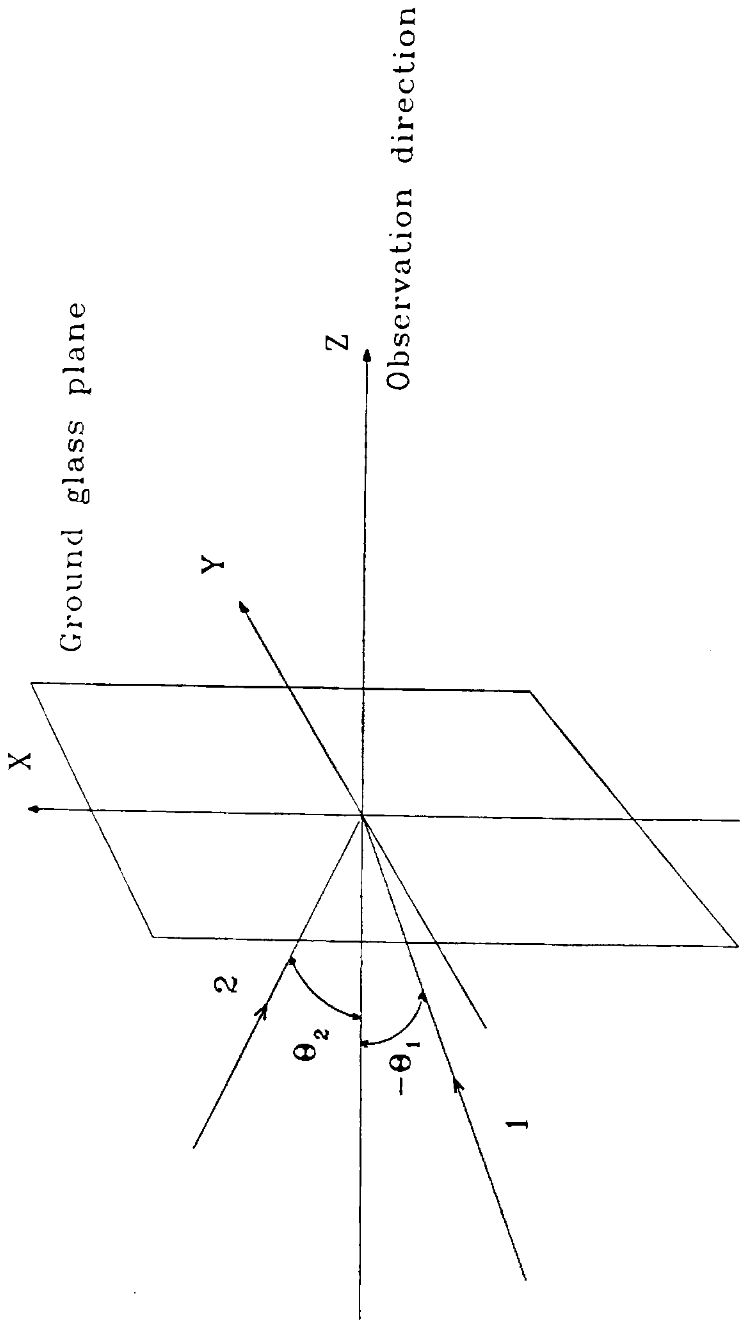
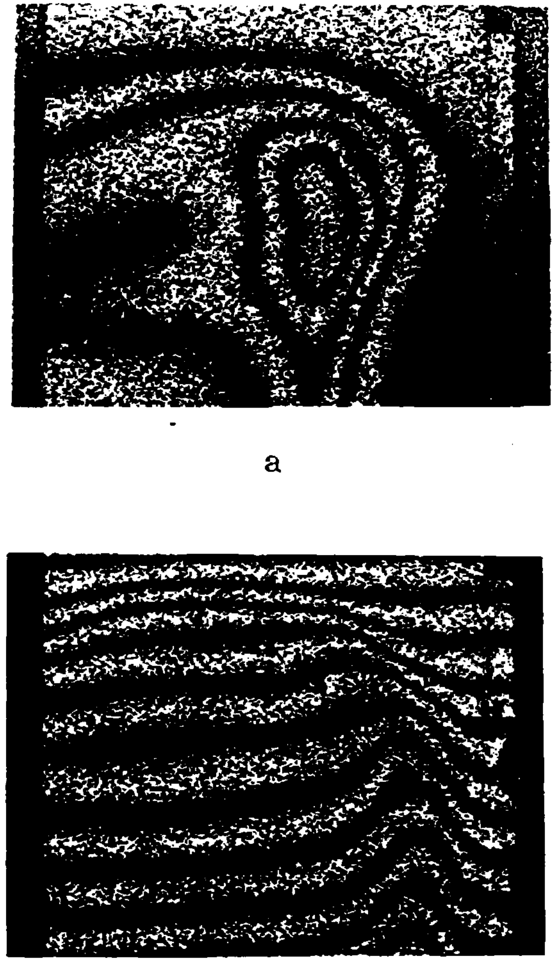

Ground glass plane
Observation direction
Z
Y
X
2
1
Θ_2
$-\Theta_1$

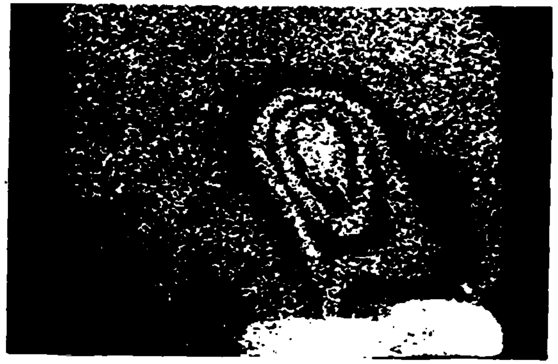
Fig.2



a

b

Fig.3



a

b

Fig.4

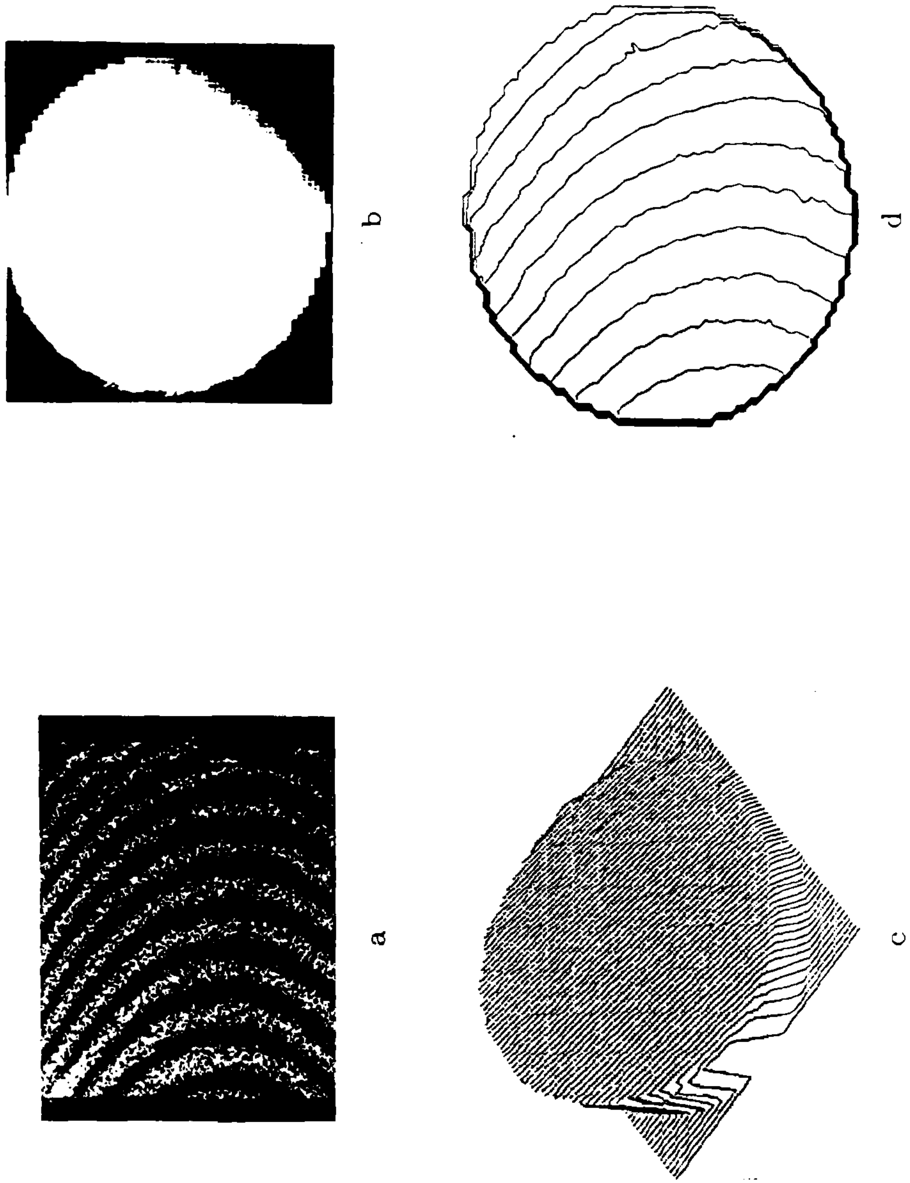


Fig.5