Optical interferometric studies of a confined liquid free surface: meniscus-effect compensation and time evolution of the surface

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Abstract. A fruitful approach to the studies of a liquid free surface is demonstrated. Using optical interferential techniques, the free surface of nonvolatile and volatile confined liquids is analyzed. Various wall container types are investigated. Besides the classical plane wall, experiments are performed by using cylindrical and toroidal walls. In these last cases, the meniscus effect that affects the free surface of the liquid is compensated. Then, it is possible to obtain completely flat free surfaces of liquids up to 80% of their total. Interferometric experiments are also described to measure the inclination of the site with respect to the local horizon, represented by the liquid flat free surface, and to follow the temporal evolution of such free surfaces affected by different conditions.

Subject terms: optical interferometry; optical free surface; meniscus compensation; optical liquid level.

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1 Introduction

As is well established, the free surface of a confined liquid is not a plane. In the case of a container of large dimensions, however, it is possible to consider that a small portion of the free surface be planar. To some extent, this small portion is located at the central part of the entire liquid surface.

Nevertheless, in some particular and practical situations it is convenient or necessary that all of the free surface be a plane, in spite of the fact that the container had small dimensions. These cases are present in the studies of aged liquid surfaces or evaporation produced at liquid surfaces. In addition, planar free surface of liquids are important factors in the design and development of high accuracy levels.

Various optical methods were introduced to experimentally analyze the different physical phenomena that occur at the interface of two media. Holographic interferometry,[1] differential interferometry,[2] and ultrasonic holography[3] can be cited as examples. The free surface of a liquid has also been used as a metrological reference surface.[4–6]

In this paper, we offer

1. a new experimental solution to obtain plane free surfaces of confined liquids in small containers
2. the use of such an approach in the development of an optical device of very small dimensions to check in a real-time mode the flatness of the liquid free surface
3. the possibility to follow up the temporal evolution of the free surface of a confined volatile liquid due to its evaporation
4. the possibility to follow up the changes in the horizontal position of small pieces in a real-time mode.

The experimental results obtained with the liquid-optical device are the magnitude, the direction, and the sign of the angular changes of the liquid surface. The threshold of the sensitivity of the overall device is $\Delta = \pm 7 \times 10^{-6}$ rad.

As a first step, a container with toroidal borders confining nonvolatile liquids was studied. A loading tube serves to load

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and unload the liquid into the cavity of the container. The loading process was followed by optical interference and the interferometrical information was real-time recorded and each image was digitally processed.

The free surface of the liquid can be considered as a phase object and then the monochromatic light reflected and refracted on it contain information related with its topography. Such information can be revealed by simple interferential techniques.

The dynamic analysis of such optical information, however, presents a high degree of complexity, because it is necessary to control a large number of experimental parameters to achieve quantitative evaluations of acceptable quality.

2 Description of the Experimental Method

The topological shape of the free surface of a confined liquid depends on the equilibrium of the gravitational and capillary forces. Formally, they depend on the capillary constant a value and the contact angle formed between the liquid surface and the container wall. In the case of a plane vertical wall, the profile of the liquid free surface is expressed as

$$x=\frac{a}{\sqrt{2}}\cosh^{-1}\left(\frac{\sqrt{2a}}{y}\right)-a\left(2-\frac{y^2}{a^2}\right)^{1/2}+x_0\ ,$$

where x_0 is determined taking into account that $(dy)/(dx) = -\cot\theta$ at $x=0$, and that y vanishes at $x\rightarrow\infty$ (Ref. 7).

Nevertheless, it is impossible to develop a plane liquid free surface using plane vertical walls because of the influence of meniscus. Because of that, to obtain a plane liquid free surface it is necessary to introduce a cylindrical wall. Figure 1 answers this question. If the level of the liquid inside of the container is equal to h, its free surface will form with the geometrical tangent to the cylinder an angle α whose value will be equal to Θ. In that case, the influence of the meniscus is compensated by the wall, and the liquid free surface will be completely flat.

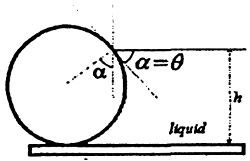

Fig. 1 When the surrounding walls have cylindrical shape, it is possible that $y=0$ (horizontality) when $\alpha=\theta$.

If the level of the liquid is lower or higher than h, the shape of the surface will appear as concave or convex according to the wetting function of the liquid-cylinder interface.

Assuming that the topological shape of the free surface is flat, it is possible to use it as a horizontal reference plane. Then, a container whose bottom is a transparent optical plane-parallel window can serve as an interferometrical level. Figure 2 describes the experimental setup.

The He-Ne laser and the inverted telescope with spatial filter provide a well-collimated monochromatic light beam. By using a front surface mirror, the plane wave illuminates the liquid container from the top. A beamsplitter collects the light waves coming from the free liquid surface and from first plane optical surface at the bottom of the container. A CCD TV camera captures the interference between both waves, sending the signal to the real-time image processor.

The liquid container is a 70- × 50-mm plastic rectangular cavity, whose walls are formed by cylindrical glass rods 8 mm in diameter. The container is sealed at its bottom by a plane parallel glass plate 10 mm thick and $\lambda/10$ flat. The entire container is located on a platform that is horizontally aligned using appropriate fine screws. Inside the described cavity, the toroidal ring is mounted, simply supported by the bottom glass plate. The dimensions of the toroidal ring are 5.4 mm for section diameter and 16.8 mm for the inner diameter.

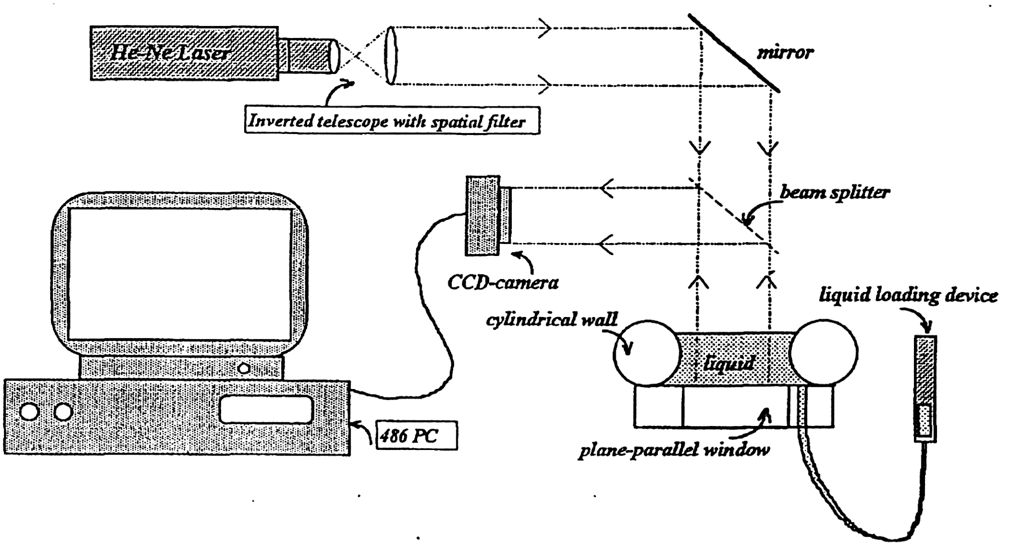

Fig. 2 Experimental setup.

The platform is conveniently isolated to avoid mechanical perturbations. It was designed and constructed as a hydraulic device to load and unload liquid to or from the container, respectively, which enables changes in the liquid free level surface with an accuracy $\Delta h = \pm 100$ nm, without perturbing the surface.

The different kind of experiments and measurements were performed using silicone oil (Dow Corning Fluid 350). At 25°C it has the following physical characteristics: viscosity = 350 cS, density = 0.97 g/cm^3, refractive index = 1.403, and surface tension = 21.1 dyn/cm (Ref. 8).

As long as the container is loading with the liquid, the free surface adopts different topologies: concave, plane, and convex, as shown in Fig. 3. Such surfaces act as mirrors that change shape according to the liquid level. When h reaches the appropriate value to compensate the meniscus effect making $\alpha = \theta$, the free liquid surface will be flat. This position is considered to be the setting point of the device. If the base platform on which the device is mounted adopts the horizontal position, the interference fringes that are observed while the free liquid surface shape is modified by loading liquid into the container appear as a symmetric pattern. This fact is assumed as to be the best criteria to fill the container until α is equal to θ. In addition, near the setting point, the fringes in the interference pattern become wider and more and more spaced, but they always maintain their symmetry.

3 Experimental Results

As mentioned before, when the liquid entering the container adopts level positions deeper or higher than h, the free surface looks like concave or convex mirrors. Then, the interference pattern observed on a screen changes according to the amount of liquid loaded into the container, as shown in Fig. 4(a). Figure 4(b) shows pictures of the interference pattern that demonstrate various steps of the loading operation of the container.

Figures 5, 6, and 7 are pictures of the interference pattern produced with the device. In these experiments, those surfaces that are less than 0.633 μm from a geometrical plane are accepted as "flat" surfaces. Obviously, 0.633 μm is the wavelength of the red He-Ne laser used to illuminate the device.

Figure 5 corresponds to the rectangular container 50 mm wide and 70 mm long with vertical plane walls. The interference pattern is deformed because of the lack of flatness along the entire free liquid surface. The zone that can be considered as a plane is less than 28% of the total surface.

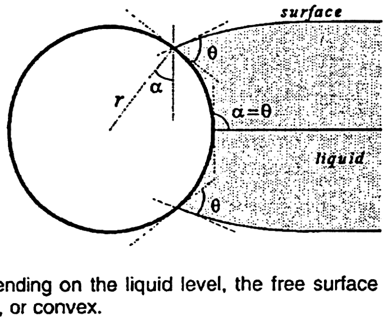

Fig. 3 Depending on the liquid level, the free surface will be concave, plane, or convex.

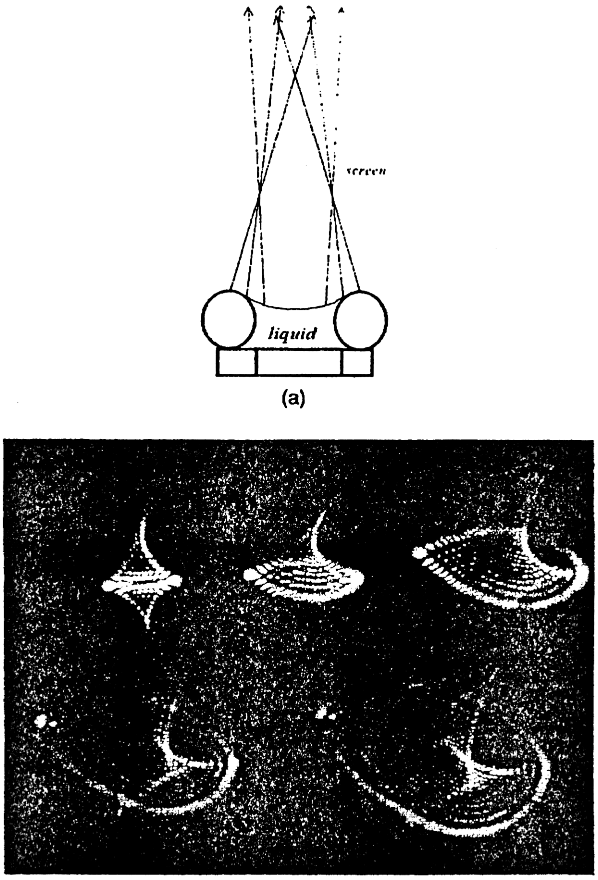

Fig. 4 (a) Free surface looks like a concave mirror. (b) Interference pattern follows the liquid-loading operation.

Figure 6 corresponds to the same sized rectangular container but with circular cylinders acting as walls. In spite of the fact that the liquid level did not reach a high enough altitude h to be $\alpha = \theta$, the zone that is considered a plane is almost 37% of the total surface.

Figure 7 corresponds to the same experimental setup as that of Fig. 6, but the level of the liquid is almost that for

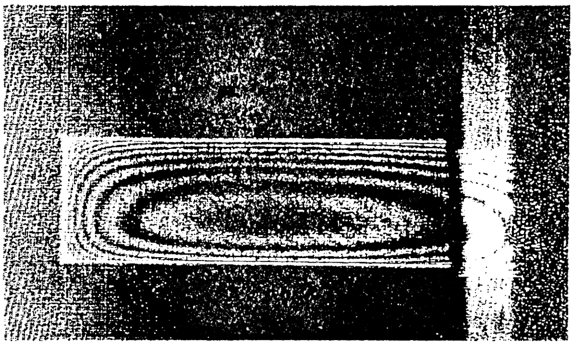

Fig. 5 Interference pattern observed in a plane walled container of rectangular shape. The flat portion of the entire surface is less than 28%.

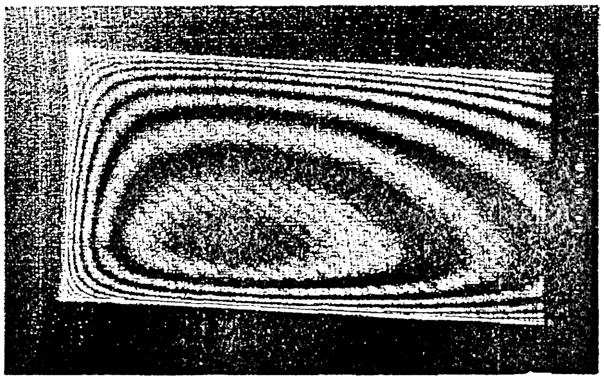

Fig. 6 Interference pattern observed in a circular section walls container of rectangular shape. The flat surface is almost 37%; $\alpha < \theta$.

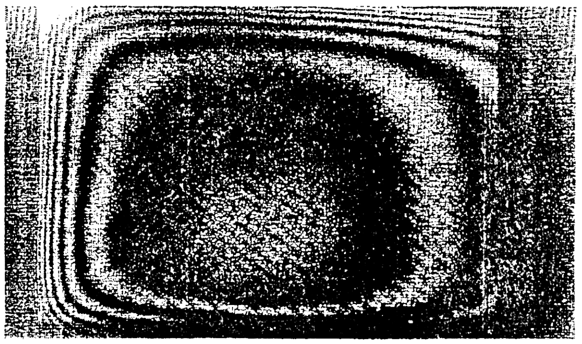

Fig. 7 Same as Fig. 6. The flat surface is 80%; $\alpha \approx \theta$.

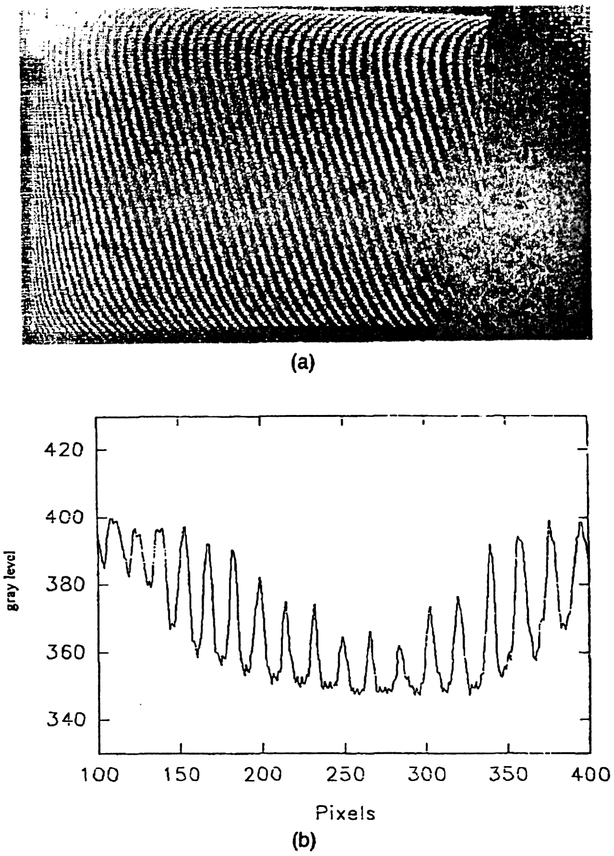

Fig. 8 (a) Electronic picture and (b) densitometric trace to measure inclination changes of the optoliquid device.

which $\alpha = \theta$ and the effect of the border is compensated to observe a plane free surface. In this case, 80% of the total surface can be considered as a plane. In addition, because this planar zone of the free surface represents the horizontal plane of the site, it was possible to measure the inclination of the optical window at the bottom of the container. The angles of inclination are $\varphi_x = 7.5 \times 10^{-6}$ rad and $\varphi_y = 8.1 \times 10^{-6}$ rad in the x and y directions, respectively.

If the mounting base of the liquid-optical device is arbitrarily inclined, it is easy to measure its lack of horizontality.

Figure 8 is a picture of the interferential pattern observed and its densitometric profile captured by perpendicularly scanning the fringe family. Measurements resulted in inclination of $\varphi = 3.1 \times 10^{-4}$ rad in a direction that forms an angle of 19.5 deg with respect to the x axes.

Figures 9, 10, and 11 correspond to a series of consecutive pictures that demonstrate the temporal evolution of the interferential pattern. Along the time of observation, the effect of the meniscus was compensated by maintaining $\alpha = \theta$. Every picture shows the fringe patterns and their corresponding densitometric traces. Fringes, that are equally spaced by e, are identified by correlative digits representing the interferential order with respect to the center of the patterns, as shown in Fig. 12.

These observations enable us to demonstrate that evaporation is preferentially produced at the middle of the free surface. In fact, comparing the consecutive temporal pictures it is easy to observe that fringes corresponding to equal liquid thickness appeared at distances farther and farther from the center of the pattern. In addition, in these zones of the liquid free surface the distances between fringes are also greater and greater as a function of time. Thus, the evaporation phenomena begin at the middle of the liquid free surface and slowly propagate to the borders of the container, as stated before.

4 Conclusions

A method to compensate the effect of the border to obtain a plane free liquid surface appears to be of great interest in studying the properties of fluids. It enables us to easily perform experiments at the laboratory, on which can be assumed conditions of infinitely extended surfaces by using, in fact, very small containers.

The liquid-optoelectronic device is easy to build and is versatile and flexible to use. It acts as an interferential liquid level, the performance of which represents progress with respect to other liquid levels.[9–11] The proposed device is also very stable from the mechanical point of view and the method has an extended range to observe and measure different kinds of effects with a threshold sensibility at least 10 times greater than others.

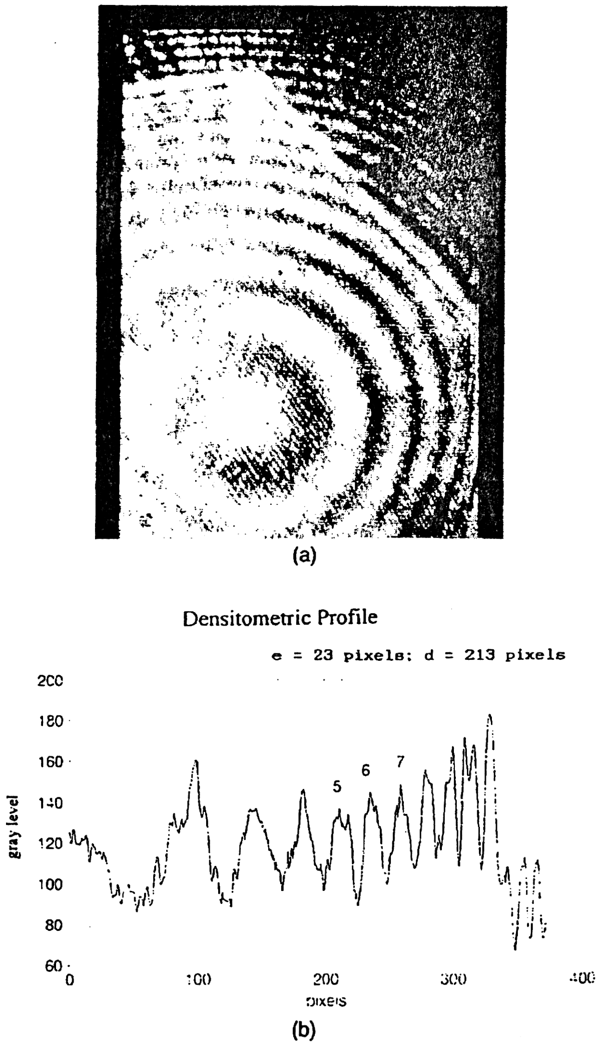

Fig. 9 (a) Electronic picture and (b) densitometric trace. Fringes 5, 6, and 7 are equally spaced.

In addition, this device could be employed to measure surface tension, the constant of capillarity, and other interesting parameters of fluids in an ample range of temperature and pressure conditions.

Acknowledgments

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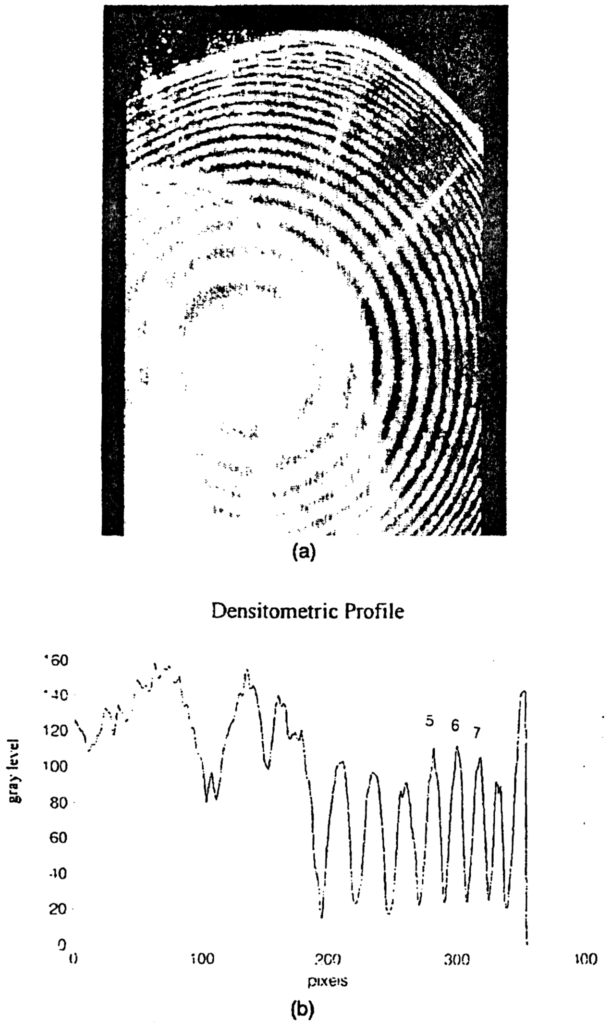

Fig. 10 (a) Electronic picture and (b) densitometric trace. Fringes 5, 6, and 7, which are equally spaced, are moved from the center to the border of the container because of liquid evaporation.

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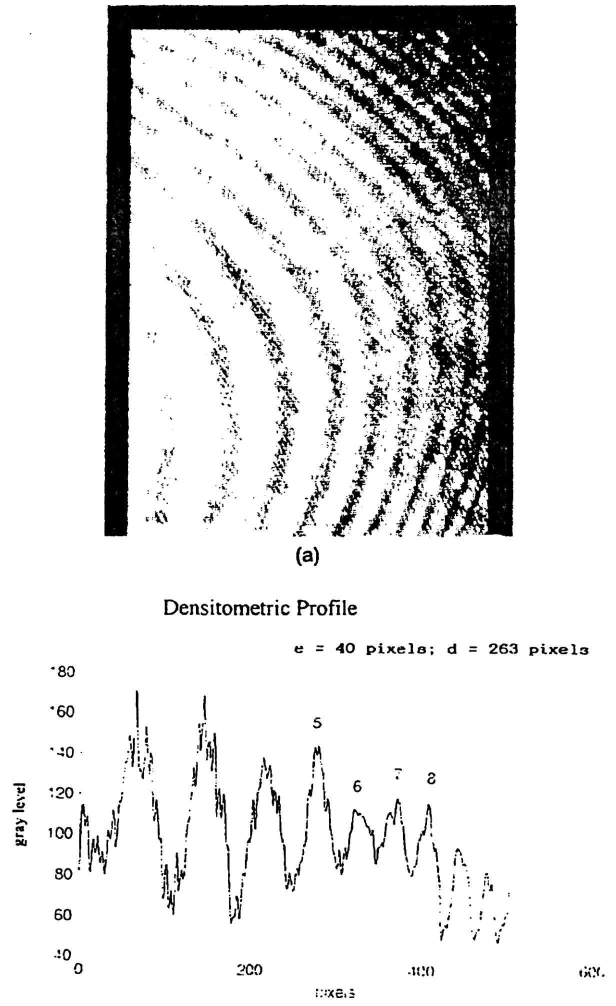

(a)

(b)

Fig. 11 (a) Electronic picture and (b) densitometric trace. Fringes 5, 6, 7, and 8, which are equally spaced, are near the border.

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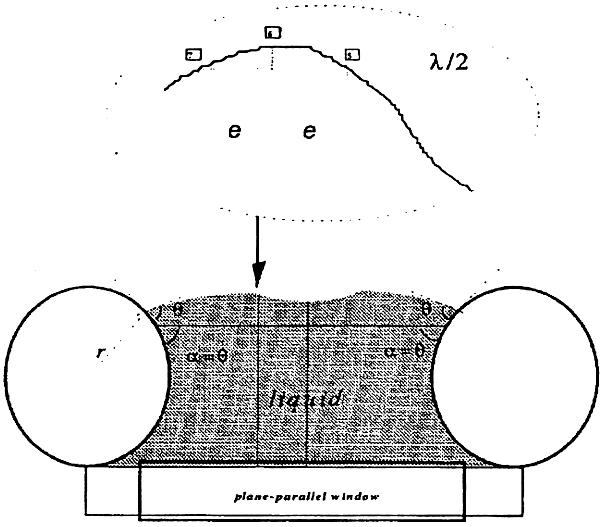
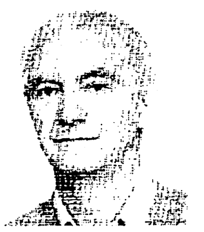


Fig. 12 Fringes 5, 6, and 7, which are equally spaced by *e*, migrate from the center to the border of the container because of liquid evaporation.

Lía M. Zerbino: Biography and photograph appear with the paper "Optical processing by birefringence modulation" in this issue.



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