Dynamic study of a Varioptic variable focal lens

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ABSTRACT

We present real-time measurements of the wave front distortion induced by a variable focal lens. This lens, called Varioptic, is made of a transparent cell filled with twin liquids. We submit a 4.5mm in diameter lens upon a 110V voltage step inducing a optical power shift of about 25 dioptries (m^{-1}) . Characteristic response time is shown to be of the order of a few 1/100s, the lens recovering its full quality after 5/100s. We present a scaling analysis of this response time versus lens size.

INTRODUCTION

Many designs of a variable focal lens have been proposed in the past: In the 40s Graham [1] showed a deformable cell filled with a fluid with an external pump, a principle which gave rise to many variations. More recently a liquid crystal slab was shown to produce small variations in focal length [2,3]. Another way appeared in the past years, through electrowetting control of liquid interfaces [4,5]. This technology, called Varioptic, uses two non-miscible fluids which are trapped in a transparent cell. The electrowetting phenomenon is used in order to move the contact line, which is the line where the liquid-liquid interface intercepts the solid supporting surface.
This basic principle was shown to work effectively, presenting a large optical power variations: for a 5mm diameter lens, the inverse focal length can vary up to 50 dioptries, with a good optical quality. Excellent reversibility and fast response were demonstrated by the first prototypes of such lenses. Since a few years, progress has been made and new generations of prototypes have come out. In this paper we present a detailed quality analysis in the dynamic regime. For that purpose a conventional interferometric equipment couldn't be used, as the wavefront changes induced by the Varioptic lens are too large to be measured using a single reference surface. We thus used an absolute wavefront analyzer working on the Schack-Hartmann principle (Model Haso 64 from Imagine Optics, France). This enables us to follow the wave-front distortions during the liquid evolution in real time.

This paper is organized as follows: the first section will present the Varioptic lens basic performances. The second section is devoted to the experimental set-up. The results will constitute the 3rd section, followed by a discussion in section 4.

1-PRESENTATION OF THE LENS

The Varioptic lens principle, detailed in the preceding paper [4], is based on electrowetting phenomenon: an electric voltage applied between a water drop and a substrate induces modification of contact angle of the water-oil interface on

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the solid substrate. Whereas in the reference [4] the substrate was a planar one, the lens considered in this paper presents a different geometry, shown on the figure 1: the supporting surface is a conical surface at the edge of the liquid cell. At zero voltage the interface reaches the opening of the cone (continuous line on fig1). When voltage is applied, the contact line goes deeper and deeper in the cone (dotted line on fig.1). This new geometry brings the advantage that the supporting material is not necessarily transparent, here stainless steel. As a consequence the lens exhibits an optical power variation from negative (diverging lens, corresponding to the continuous line on Fig 1) to positive (discontinuous line on the figure), the total variation in dioptries being unchanged. Another advantage is that this geometry is self-adjusting: at rest the hydrophobic liquid is spontaneously filling the conical cavity, the edge of the oil reaching the top of the cone, making this operation easy.

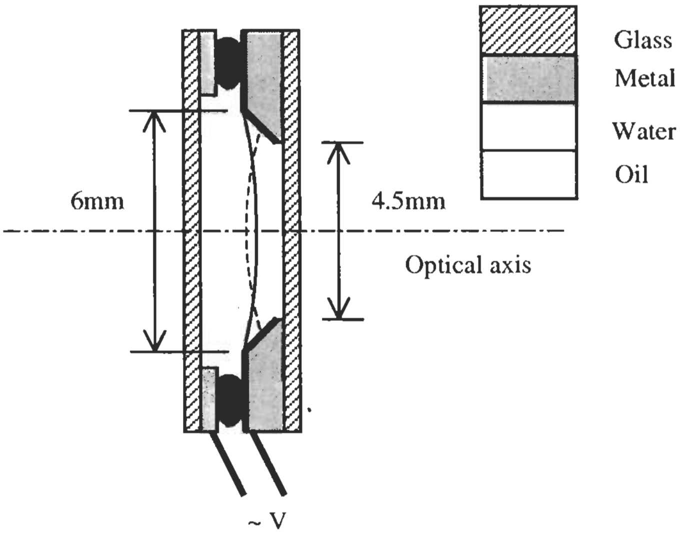


Figure 1:schematics of the Varioptic lens: the electric voltage changes the curvature of the liquid-liquid interface through electrowetting phenomenon.

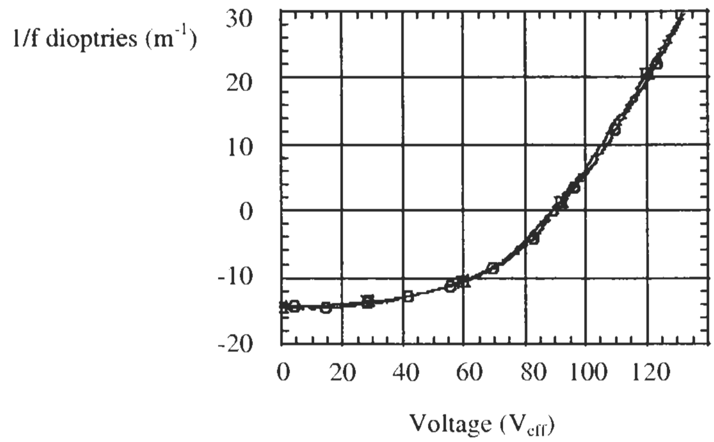


Figure 2: typical response curve of the inverse focal length versus applied voltage (ac, frequency 5kHz).

Figure 2 presents a typical curve for the inverse focal length versus voltage. This curve is obtained by a simple tracking of the laser focalization upon a voltage cycle: rounds (respectively squares) show increasing (respectively decreasing) voltage. No detectable hysteresis is measured from this curve. The driving voltage is compatible with the expected variation of contact angle predicted from the simple electrowetting theory [6,7]. The frequency of the a.c. voltage used for recording fig. 2 is 5kHz. The electrical characteristics of the lens are comparable to a capacitor (slightly variable) of about 30pF, with a quality factor of about 20-40. This makes the dissipated power inside the cell about 1mW.

2-EXPERIMENTAL SET-UP

The figure 3 shows our experimental set-up:

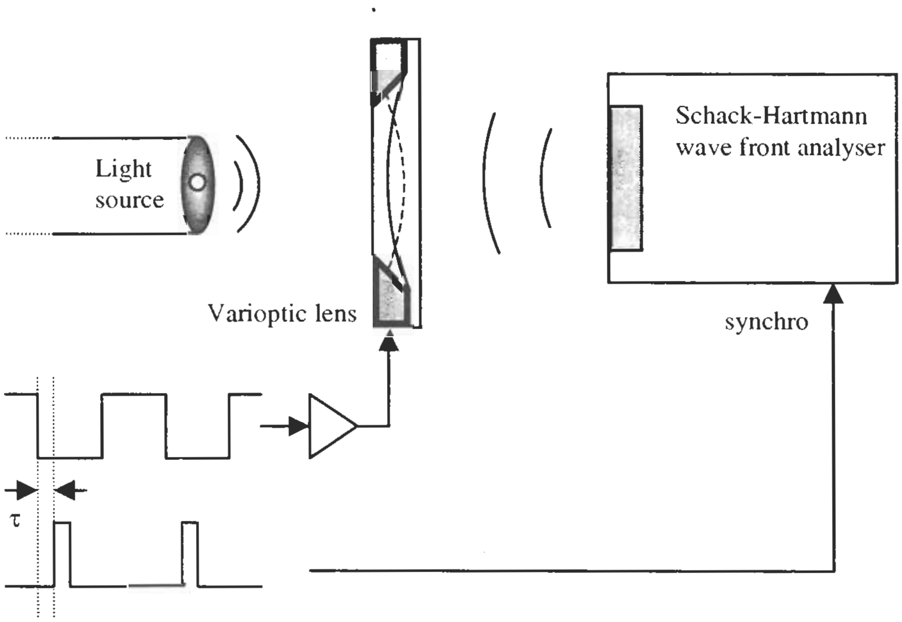


Figure 3: schematics of the experimental set-up for a dynamic wave-front measurement using an HASO wave front analyzer (Imagine Optics, France).

The light beam, emitted by a single mode optical fiber travels the Varioptic lens and is further analyzed by the wave front analyzer. The lens and analyzer positions are chosen such that the beam size matches the sensor area.

The analyzer HASO-64 (Imagine Optics, France) is based on the Scharck-Hartmann principle : A 64x64 microlenses array focuses the beam on a CCD sensor at the focal plane of the lenses. For each lens, the position of the focus point relative to the optical axis allows to determine the local slope of the wave front. The shape of the wave front is calculated by integration. The great advantage of this measurement is that it does not require a reference surface.

The optical fiber end is assumed to be a pinpoint source and the wave front before the lens is spherical. The lens, focusing the beam, modifies the wave front curvature and introduce distortions. The mean curvature radius of the wave front measured by the analyzer allows to determine the position of the image of the source and also to calculate the focal length of the lens.

In order to analyze the dynamic response, a voltage step is applied on the Varioptic lens, inducing an abrupt change of the liquids interface shape. Such a periodic step is applied periodically to the lens. The analyzer camera acquisition is triggered with a fixed delay compared to the rising front of driving voltage. Tuning the delay for one experiment to another allows to follow the shape of the wave front during the transient regime.

3- EXPERIMENTAL RESULTS

Figure 4 shows images of the wavefront measured at the output of the Varioptic lens after an abrupt voltage step from 110V to 0V. This voltage step induces a change in focal length corresponding to 26 dioptries. Pictures caught at different delays after the driving step allow to follow the evolution of the wave front during the transient regime. Because the pupil of the lens is constant and the power of the lens depends on the driving voltage, the illuminated area is changing on the CCD sensor. The irregular shapes of the intermediate measurements correspond to intermediate times, where the wave front is largely affected.

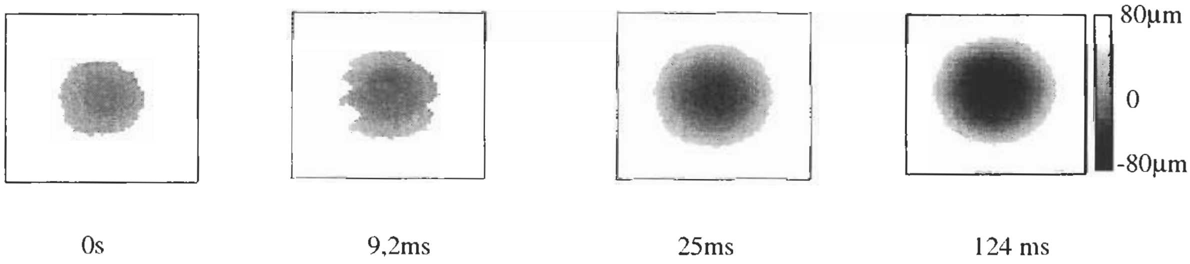


Figure 4:Wavefront topography at the output of the Varioptic lens, at several times after voltage step.
The gray scale is the same for all pictures.

Figure 5 shows the wavefront curvature as a function of time after the same voltage step than above: from 110V to 0V abruptly. Starting value corresponds to 110V, and final stage to 0V. At short time, the focus evolution seems chaotic. After 30 ms 90% of the focus step is achieved . Then an exponential relaxation occurs.

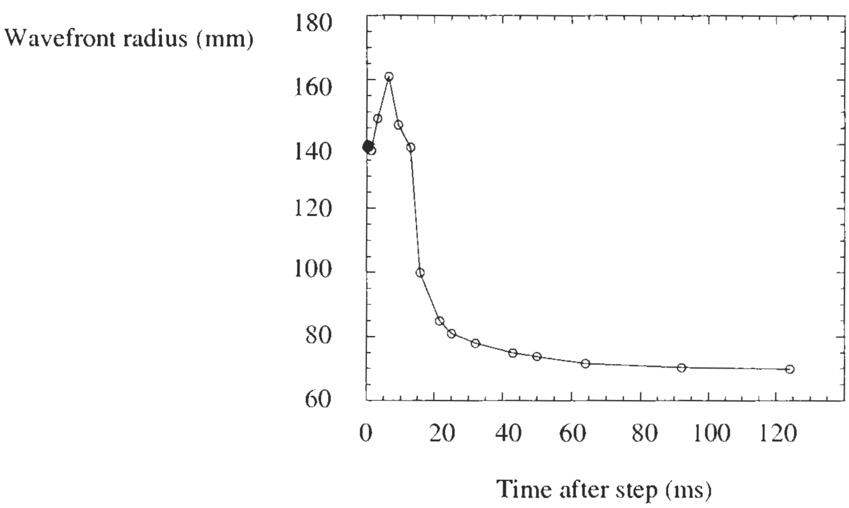
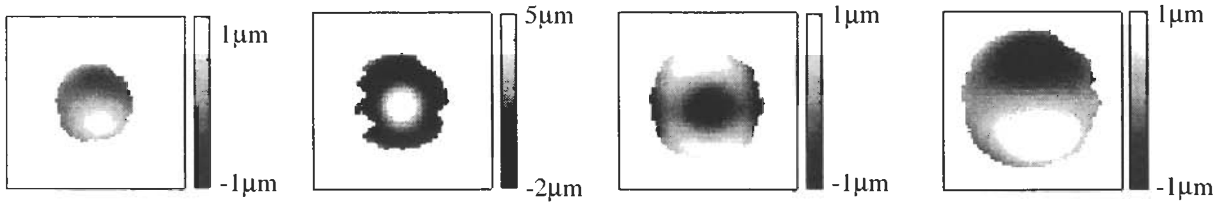


Figure 5: Radius of the wavefront after the lens, as a function of time.

From the data recorded above, one can also extract the deviation from perfect spherical wave-front by subtracting numerically the best approaching spherical shape. This leads to the Figure 6, which presents the evolution of the wave front distortion. Again the size of the beam is changing, due to a different geometry of the light beam, depending on the focal length of Varioptic lens. First and last images show the situation before and after the step. They can be considered as static measurements. During this regime a coma aberration is visible, due to gravity effect: a spurious 1% mismatch in liquid densities induces a deformation of the oil-water interface from the spherical shape.



0s, PV=1.3µm 9.2ms, PV=7.9 µm 25ms, PV =2.0 µm 124 ms, PV=2.0 µm

Figure 6: Wavefront distortions (curvature has been subtracted) at several times after voltage step.

Figure 7 shows the amplitude (peak to valley) of the distortions measured from the data above, as a function of time. One observes clear oscillations, indicating that inertial effect are present in the hydrodynamics of the drop shape changes.

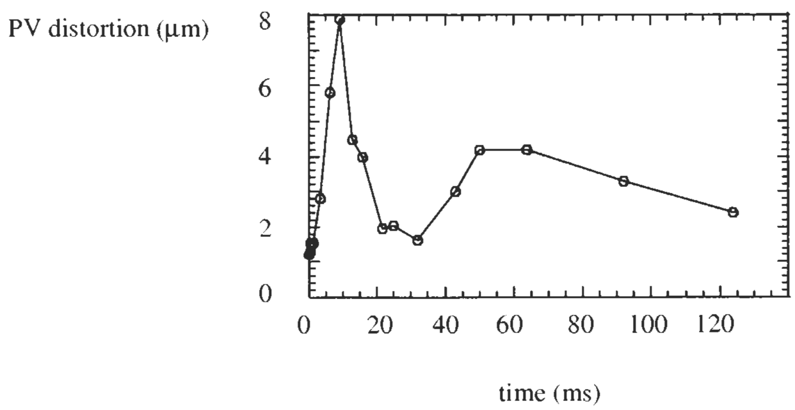


Figure 7: Distortion of the wavefront after the lens, as a function of time.

4- DISCUSSION

Our results confirm that the characteristic time for the relaxation after a single change in focal length is of the order of a few10^{-2}s or less for a 5mm diameter lens. The additional information we have obtained here is the time it takes for the full quality recovering: about 4-5 10^{-2}s. Of course the time evolution showed in the figure 7 exhibits oscillations, which suggests that a better dynamical response could be obtained with more viscous liquids: In this publication we didn't adjust the viscosity in order to be right at critical damping. This should be done to get the fastest response.

Theoretical estimate of the response time

One can estimate the response time as follows: the driving force of a focal length change comes from the capillary forces $\Delta\gamma_{s-w}$ due to the change in voltage, where γ_{s-w} is the solid-liquid interfacial tension, which is modified by electrowetting. In our case, for a change from 0V to 110V, one can estimate $\Delta\gamma_{s-w}$ from the ref [6]:

$$\Delta\gamma_{s-w} = 1/2\ \varepsilon\varepsilon_0/e\ V^2 \quad (1)$$

, leading to $\Delta\gamma_{s-w} = 10$ mN/m in the present case. Against this driving force acts the dissipation, which comes from hydrodynamics through the viscosity. In the lens shown here, the viscosity of the water solution was: $\eta = 20\ 10^{-3}$ Pa s , the oil being less viscous. As in reference text books [8] one can form a characteristic speed of a contact line with a combination of the driving force and the dissipation:

$$V = \Delta\gamma_{s-w}/\eta = 0.5 \text{ m/s}. \quad (2)$$

This is the typical velocity that the contact line can reach during a change in the drop shape. If we suppose that this line should move over distances of about 1 mm, this leads to a time of τ=2ms, a bit shorter than the measured response time.

Tuning of the viscosity

In the above estimations we didn't take into account inertial effects. This sometimes leads to an oscillatory response of the lens, as in the ref [4]. In order to damp these oscillations, one should adapt the viscosity of one of the two fluids. Oscillations involve waves at the liquid-liquid interface. By considering classical treatments of this problem [9] one can derive that the critical damping is given by a viscosity:

$$\eta_{crit.} = \alpha\ (\ \rho\gamma_{w-o}\Phi/(2\pi)\ )^{1/2} \quad (3)$$

where Φ is the lens diameter, ρ is the liquid density γ_{w-o} is the liquid-liquid interfacial tension, and α is a numerical factor which depends upon the exact geometry of the cell. From our previous experiments, one can attribute α=0.2.

Scaling law with lens size

In this paragraph, one should address the question of size dependence of the response time. If we suppose that one is able to adjust the viscosity of the fluid to its best value (the critical value), then the response time should vary according to the distance that the contact line translate, which is proportional to the size Φ, divided by the speed of the contact line V, given by equation (2): As a result one finds the following size dependence of the response time:

$$\tau\ \alpha\ \Phi^{3/2}. \quad (4)$$

CONCLUSION

The preceding experiments show results about a new component for optics: Varioptic's variable focal lens. We have investigated the quality of the lens during a voltage abrupt change. In this regime, it was found that the response characteristic time of the lens is of the order of 2/100s, the full quality of the lens being restored after 4/100s. We showed that an oscillatory response is obtained, such that a faster response could be if the viscosity was tuned just at critical damping. The question of the harmonic regime, i.e. when the lens is submitted to sinusoidal solicitations remains open, the data shown above can give estimates of the scanning speed that could be used with Varioptic technology.

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