Low-Power Laser Deformation of an Air-Liquid Interface

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We report on the deformation of an air-water surface with a totally reflected low-power laser beam, inducing a convex mirror effect on the beam propagation. This bending is stronger close to the critical angle and depends on the polarization of the laser light. A model, leading to a simple dependence between the Goos-Hänchen shift and the radius of curvature of the interface, supports these observations. Bendings with radius of curvature as low as 0.10 m are demonstrated.

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Optofluidics is a new promising growing field [1,2]. Its remarkable reconfigurable and adaptive properties are essentially provided by the flexibility of fluids. However, since the pioneering work of Ashkin and Dziedzic on radiation pressure [3], it is well known that deforming an air-water interface with a laser beam is difficult, because of the high surface tension of water. To tackle this problem, two main directions have been explored. The first one uses relatively high power laser to deform the interface [3,4], which is sometimes hardly manageable, whereas the second one uses an interface between two liquids having similar surface tension [5–7]. Even at oblique incidence, due to the continuity of the Snell laws [8], the resulting radiation pressure force is always normal to the interface. Yet, total internal reflection is not specular since there is a small longitudinal shift of the reflected beam at the interface [9]. This so-called Goos-Hänchen shift may induce a nonzero horizontal component of the radiation pressure force on the interface. One may then wonder whether, even with low laser power, this shift may deform the air-water interface. The aim of this Letter is thus to explore such a deformation under laser illumination and to investigate the possible resulting consequences and applications.

Let us consider an air-liquid interface. To be under total reflection conditions, the light beam must come from below the interface. We have thus made a water layer with a thickness varying from 0.4 to 2 cm, with a metallic mirror underneath (see Fig. 1). The higher limiting surface is the air-water interface. The temperature of the experimental set up is 21 °C. A glass tube (T_1) closed with a quasiperpendicular silica window enables to inject the laser light in the water. The light undergoes a metallic reflection on the mirror and is totally reflected on the interface if the angle of incidence θ is greater than the critical angle $\theta_c = 48.75°$. Then it goes back to the mirror before being out coupled by another glass tube (T_2). Using the various reflections under partial reflection conditions, we estimate the parallelism error between the mirror and the interface to be less than 2.0×10^{-5} rad.

The laser is a commercial 20 mW argon laser oscillating at $\lambda = 514$ nm. A half wave plate (HWP) can change the linear polarization of the light. The half beam size of the laser impinging on the interface is $w = 0.68$ mm and is within the Rayleigh zone [10]. We deduced the bending of the water surface by looking at the curved mirror effect on the Gaussian laser beam itself. The beam profile is measured 25 cm after total reflection either with a beam profile analyzer (D) or by taking a picture. Figure 2 shows such pictures of the laser spot for an angle of incidence $\theta = 49.30°$, together with its Gaussian fit.

Surprisingly, while for metallic reflection the laser beam remains circular, for total reflection, the laser beam is clearly and strongly elliptical both for TE and TM polarizations. However, the intensity profile remains Gaussian. The profile is larger in the x axis, which is in the plane of incidence, whereas in the y axis, i.e., perpendicular to this plane, the profile seems to be unchanged compared with metallic reflection. This means that the surface bending should correspond to a convex cylindrical mirror, i.e., a small elliptical dip on the water surface, mainly elongated

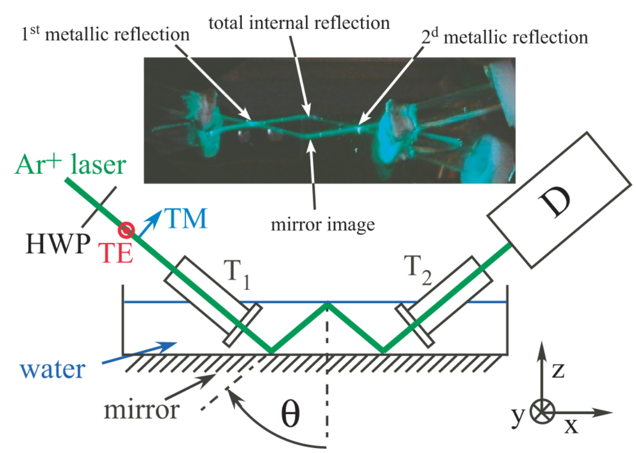

FIG. 1 (color online). Experimental setup. TM: linear polarization in the x-z plane, TE: linear polarization along y. Inset: picture of the setup.

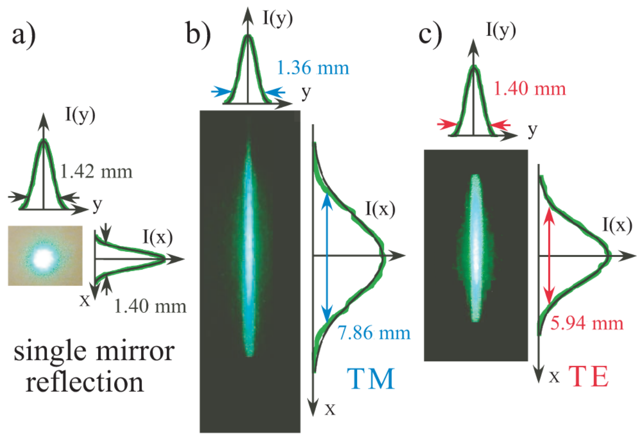

FIG. 2 (color online). Picture of the laser spot, laser profile (green) and Gaussian fit (black) after: (a) mirror reflection without water; total reflection on the water surface for (b) TM, (c) TE. Error on the fits: less than 0.03 mm.

along the y axis. Moreover, the intensity profile is wider and thus the deformation is bigger for a TM than for a TE polarized laser beam. Besides, the laser beam is less defocused as the angle of incidence increases and conversely, the deformation is bigger as the angle of incidence gets closer to θ_c. On partial reflection, we have noticed that the beam keeps its cylindrical symmetry and is thus unaffected. This suggests that the liquid surface deformation and the Goos-Hänchen effect [8,9] are strongly correlated. We have checked that the thickness of the water layer does not have any influence. We have also varied the laser power from 1 to 20 mW. Curiously, the bending does not seem to depend on the laser power. Let us now try to build a simple geometrical model of the deformation.

We consider a Gaussian beam totally reflected on the water interface. For the sake of simplicity, we only take into account the variations in the x direction. The reflected beam undergoes a longitudinal Goos Hänchen shift δ, i.e., along the x axis. Then, a small surface ds of the interface experiences a radiation pressure force $d\mathbf{F}_r$:

$$d\mathbf{F}_r = dF(e^{-2(x+\delta/2)^2/w^2}\mathbf{e}_{in} - e^{-2(x-\delta/2)^2/w^2}\mathbf{e}_{\rm out}), \quad (1)$$

where $\mathbf{e}_{\rm in}$ and $\mathbf{e}_{\rm out}$ are unitary vectors along the incident and reflected beam, respectively, and $dF = P_r ds \cos\theta$ (P_r is the maximum radiation pressure). Assuming δ is small compared with x, one then gets

$$d\mathbf{F}_r \approx dF e^{-2x^2/w^2}\left(2\cos\theta\mathbf{e}_z - \frac{4\delta x}{w^2}\sin\theta\mathbf{e}_x\right), \quad (2)$$

where $\mathbf{e}_x$ and $\mathbf{e}_z$ are unitary vectors along x and z. The existence of a horizontal component is responsible for the deformation. Usually, such inward forces produce a hump in the surface. However, we experimentally see a convex deformation. This is probably due to the existence of an evanescent wave above the surface which penetration depth is less than 1 μm [11]. This light intensity gradient

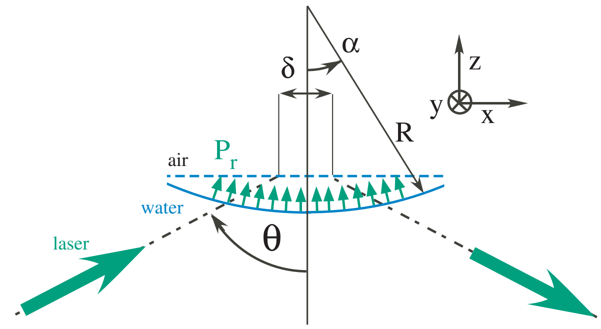

FIG. 3 (color online). Laser surface interaction showing the resulting force due to the longitudinal shift δ. The interface is perpendicular to the force. For clarity, the scale of the figure does not correspond to reality.

leads to an increase of the air pressure just above the surface which induces a dimple on the surface. Let us write that the interface has to be perpendicular to the force (see Fig. 3):

$$\tan\alpha = 2\tan\theta\frac{\delta x}{w^2}, \qquad \sin\alpha = \frac{x}{R}, \quad (3)$$

α being the angle between the z axis and the normal to the interface and R the radius of curvature. Finally, since α is small, one obtains a simple relation between δ and R:

$$2\frac{\delta}{w^2} \approx \frac{1}{R\tan\theta}. \quad (4)$$

R depends on the inverse of Goos-Hänchen shift, and on the square of the laser beam size. Because of the parabolic approximation of the Gaussian beam, this bending does not depend on the laser power. This explains why there is no deformation in the y axis, since the direction of the force is always in the x-z plane. From the same geometric arguments, the radius of curvature neither depends on the surface tension of the liquid.

In order to experimentally validate our model, we have recorded the intensity profile for several angles of incidence, for TM and TE polarizations. Using the propagation of Gaussian beams [10], we have calculated the curvature of the mirror that induces such a beam defocusing. We have then plotted $1/R\tan\theta$ versus θ, together with the theoretical Goos-Hänchen shift [8]. As can be seen in Fig. 4, the two curves vary exactly the same, for both polarizations. On partial reflection, there is no shift and then no deformation. The bending is very important close to the critical angle since δ diverges. According to Fig. 4(a), we have plotted on Fig. 4(b), $1/R\tan\theta$ versus δ. The linear dependence between the two is obvious. The proportionality coefficient is 4.6×10^6 m^{-2}, and is independent of the polarization. According to Eq. (4), this leads to a half beam size $w = 0.66$ mm, very close to the measured value $w = 0.68$ mm. Additional measurements with different spot sizes confirm our model and the approximations we did.

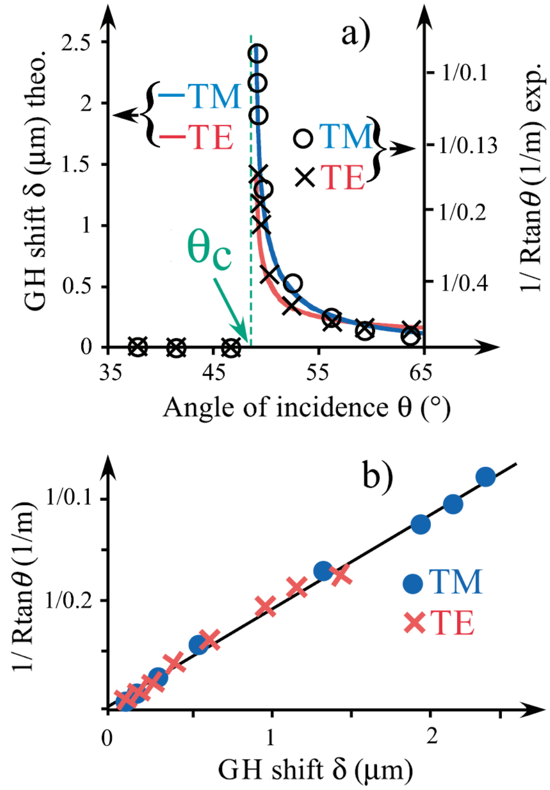

FIG. 4 (color online). (a) Theoretical shift δ for TM (blue) and TE (red), and experimental data of R (circle TM, cross TE) versus θ. (b) R versus δ. Error bars are in the symbols.

Our results may have important consequences in different domains of physics, including rheology, biophysics, and optofluidics. First, this interface bending may be an elegant way to induce reconfigurable lenses on liquid interfaces [12] with very low laser power, preventing unwanted destruction or nonlinear effects [13]. Moreover, it may open a new way of investigation in the rheology of biological cells studied by laser irradiation by controlling the stress induced on the molecular level [14,15], without disturbing the dynamics of the cell. Conversely, one can reach a nonlinear regime [6,16,17] with much lower laser power. This may then lead to new deformation shapes or dynamics. Finally, it may also shed new light on the dynamics of the formation of liquid optical fibers [18] and explain the sudden stability and rigidity of such fibers.

To conclude, we have demonstrated a new versatile and highly reconfigurable way to deform an air-water interface with a low-power laser using total reflection. Confirmed by a simple model, we have shown that the liquid curvature is inversely proportional to the Goos-Hänchen shift and independent of the laser power. Besides, since the bending depends on the laser polarization, the curvature of the surface can be rapidly changed by switching from one polarization to the other or by mixing them. Finally, this surface bending may lead to ultra compact optical devices like arrays of micro-lenses or gratings. For example, high-order Hermite-Gaussian modes [10], or Laguerre-Gaussian modes [19], can create new reconfigurable dynamical structures and micropatternings.

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