Comment on "Low-Power Laser Deformation of an Air-Liquid Interface"

Recently, the observation of low-power laser deformation of an air-water horizontal interface under total internal reflection (TIR) was argued [1]. This effect was claimed to be independent of the incident light-beam power and the interfacial tension and explained by a model that (i) accounts for the existence of a nonzero in-plane component of the optical radiation pressure exerted on the air-water interface, which was ascribed to the Goos-Hänchen spatial shift—a characteristic feature of TIR—and (ii) does not account for the force balance at the air-water interface. This Comment aims at correcting these two points.

First, the optical force acting on the interface is always normal to the interface, be the situation associated to TIR or not. To prove it, we assume the fluids $i = (1, 2)$ to be nonmagnetic, dielectric, transparent, and isotropic. Then, considering steady-state and time-averaged effects over an optical cycle, for the electromagnetic stress tensor (whose divergence gives the associated force density) is [2]

$$\mathbb{T}_i^{\mathrm{em}} = \frac{1}{2}\epsilon_0\rho_i\frac{\partial\epsilon_i}{\partial\rho_i}\bigg|_T \mathbf{E}_i^2\mathbb{I} - \frac{1}{2}\epsilon_0\epsilon_i\mathbf{E}_i^2\mathbb{I} + \epsilon_0\epsilon_i\mathbf{E}_i{}^t\mathbf{E}_i, \quad (1)$$

where ϵ_0 is the vacuum dielectric permittivity, ϵ_i the relative dielectric permittivity, ρ_i the density, T the temperature, $\mathbb{I}$ the identity matrix, and ${}^t\mathbf{E}_i$ the transpose of the electric field vector $\mathbf{E}_i$. On the one hand, the first term of Eq. (1), which refers to electrostriction, is isotropic and its contribution to the electromagnetic interfacial stress is therefore purely normal. On the other hand, the two last terms of Eq. (1) refer to the optical radiation pressure and its contribution is written $(\mathbb{T}_2^{\prime\mathrm{em}} - \mathbb{T}_1^{\prime\mathrm{em}})\mathbf{n}_{1\to2}$, where $\mathbb{T}_i^{\prime\mathrm{em}} = -\frac{1}{2}\epsilon_0\epsilon_i\mathbf{E}_i^2\mathbb{I} + \epsilon_0\epsilon_i\mathbf{E}_i{}^t\mathbf{E}_i$ and $\mathbf{n}_{1\to2}$ is the unit vector normal to the interface oriented from fluid $i = 1$ to $i = 2$. Note that the latter expression for the optical surface force density is obtained from the flux of $\mathbb{T}_i^{\prime\mathrm{em}}$ through a volume element $dV = dxdydz$ that crosses the interface at rest located at a fixed z, which gives null contributions for the side surface elements once passing to the limit $dz \to 0$, whatever the light field. Then, considering $(\boldsymbol{\alpha}, \boldsymbol{\beta})$ as two orthogonal unit vectors lying in the plane tangent to the interface at point M, $(\boldsymbol{\alpha}, \boldsymbol{\beta}, \mathbf{n}_{1\to2})$ constitutes an orthonormal basis associated with M. Expressing the electric fields in this basis as $\mathbf{E}_i = E_{\alpha,i}\boldsymbol{\alpha} + E_{\beta,i}\boldsymbol{\beta} + E_{n,i}\mathbf{n}_{1\to2}$ and noting $\mathbf{E}_{t,i} = E_{\alpha,i}\boldsymbol{\alpha} + E_{\beta,i}\boldsymbol{\beta}$, the components $(\Pi_{\alpha,i}, \Pi_{\beta,i}, \Pi_{n,i})$ of the force densities $\mathbf{\Pi}_i = (-1)^i\mathbb{T}_i^{\prime\mathrm{em}}\mathbf{n}_{1\to2}$ exerted on the interface by medium i express as $\Pi_{\alpha,i} = (-1)^iE_{\alpha,i}D_{n,i}$, $\Pi_{\beta,i} = (-1)^iE_{\beta,i}D_{n,i}$ and $\Pi_{n,i} = (-1)^i\epsilon_0\epsilon_i(E_{n,i}^2 - E_{t,i}^2)/2$ where $\mathbf{D}_i = \epsilon_0\epsilon_i\mathbf{E}_i$ is the electric displacement vector. Since Maxwell's equations imply that $D_{n,1} = D_{n,2}$ and $\mathbf{E}_{t,1} = \mathbf{E}_{t,2}$, the in-plane components of the net force density exerted on the interface, $\mathbf{\Pi} = \mathbf{\Pi}_1 + \mathbf{\Pi}_2$, are always both zero: $\mathbf{\Pi}\cdot\boldsymbol{\alpha} = 0$ and $\mathbf{\Pi}\cdot\boldsymbol{\beta} = 0$. In contrast, its component along $\mathbf{n}_{1\to2}$ is nonzero. Indeed, using the continuity of D_n across the interface and averaging over one period of oscillation of the electric field one obtains $\mathbf{\Pi}\cdot\mathbf{n}_{1\to2} = \frac{1}{4}\epsilon_0(\epsilon_1 - \epsilon_2)\times[|\mathbf{E}_{t,1}|^2 + (\epsilon_1/\epsilon_2)|\mathbf{E}_{n,1}|^2]$.

Conclusion (i): there is no contribution of the optical surface force density in the plane of the interface, in contrast to what is claimed in [1].

Second, the correct determination of the interface deformation must account for the balance forces that include electromagnetic, capillary, hydrodynamical, and gravitational contributions, which is missing in [1]. Assuming incompressible flows and a constant interfacial tension σ, the balance of forces exerted on the interface is

$$(\mathbb{T}_2^{\mathrm{hydro}} - \mathbb{T}_1^{\mathrm{hydro}} + \mathbb{T}_2^{\mathrm{em}} - \mathbb{T}_1^{\mathrm{em}} - \sigma\kappa\mathbb{I})\mathbf{n}_{1\to2} = \mathbf{0}, \quad (2)$$

where $\mathbb{T}_i^{\mathrm{hydro}} = -p_i\mathbb{I} + \eta_i[\boldsymbol{\nabla}\otimes\mathbf{v} + {}^t(\boldsymbol{\nabla}\otimes\mathbf{v})]$ is the hydrodynamic stress tensor with p_i, η_i, and $\mathbf{v}_i$ being, respectively, the hydrostatic pressure, the viscosity, and the velocity of the fluid i; $\otimes$ is the dyadic product and κ is the interface curvature. Then, Eq. (2) must be solved accounting for the linear momentum conservation in the bulk of each fluid, namely, in the Stokes regime, $\rho_i\mathbf{g} - \boldsymbol{\nabla}q_i + \eta_i\Delta\mathbf{v}_i = \mathbf{0}$ where $\mathbf{g}$ is the gravitational acceleration and $q_i = p_i - \frac{1}{2}\epsilon_0\mathbf{E}_i^2\rho_i\frac{\partial\epsilon_i}{\partial\rho_i}|_T$.

Conclusion (ii): any light-induced interface deformation is expected to depend on both the light-beam power and interfacial tension, in contrast to what is claimed in [1].

Two experimental remarks may be added. The first one is related to the fact that, obviously, no effect is expected at zero light-beam power. Therefore, the claimed independence versus the optical power in [1] points out the possible role of a residual interface curvature at rest in the original experiment, for instance a meniscus due to the presence of the immersed tubes, which is not discussed in [1]. The second remark deals with transient dynamics of the interface. Indeed, since any interface deformation is expected to settle towards steady state in a finite time duration when the beam is switched on, the observation of transient regime, not shown in [1], could be useful to prove the existence of a light-induced interface deformation.

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