

Laser-Induced Liquid Deformation Driven by the Marangoni Effect

Wei Zhang,¹ Feng Lin,^{2,3,4} Jonathan Hu,^{1,*} Zhiming Wang,^{3,*} and Jiming Bao^{4,*}

¹Baylor University, Waco, TX 76798, USA

²National Center for International Research on Photoelectric and Energy Materials, School of Materials and Energy, Yunnan University, Kunming 650091, China

³University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China

⁴University of Houston, Houston, TX 77204, USA

*Email: Jonathan_hu@baylor.edu, zhmwang@uestc.edu.cn, and jbao@uh.edu

Abstract: We studied laser-induced liquid indentations generated by the Marangoni effect. We showed experimental results along with the simulation model based on the lubrication theory. © 2023 The Author(s)

Surface deformations on liquid driven by the Marangoni effect have generated considerable research interest. Laser light can generate heat on a liquid surface, which can lead to the Marangoni effect and produce a strong gradient in the surface tension. Surface laser heating is noncontact and has the advantage of precise actuation in space and time. Radiation pressure is usually insufficient to cause significant surface deformation because it must overcome the surface tension. Earlier experimental work used lasers to thermally induce a surface tension gradient and produce surface deformation in a thin film of light-absorbing heavy oil [1–3]. However, the deformations produced were so minimal that they were hard to observe directly with the naked eye or standard photography. Subsequently, theoretical analyses were conducted focusing on non-uniform surface tension created by surface heating. It has been shown that surface tension-induced deformation can lead to a variety of applications, such as lithography and 3D printing [4], dynamic grating and spatial light modulation [5], and microfluidics and adaptive optics [6]. In this study, we demonstrated the creation of novel optothermal capillary fluids that exhibit large surface laser-induced deformations. We also developed a simulation model using the lubrication theory to explain the process of laser-induced surface deformation on liquids.

To demonstrate the Marangoni effect, we used a low-power (1 W) CW laser beam to generate a non-uniform surface temperature field [7]. Figure 1(a) shows a schematic diagram of the experimental setup. A petri dish containing ferrofluid was illuminated from above by a laser beam. Ferrofluid is a liquid that is best known for its magnet-generated surface ridges [8]. We used ferrofluid to show the strong Marangoni effect with a high light-absorbing property. The laser's wavelength was 532 nm, and a 532-nm notch filter was used to block the laser for improved imaging. Additional white light was used to illuminate the fluid for the camera. The fluid surface distortions were captured by digital cameras. We note that the deformation exhibited here is qualitatively distinct from the surface deformations previously reported in the literature, which were hard to be directly observed with the naked eye or standard photography. Due to the Marangoni effect, the fluid at the upper surface experienced a rapid outward flow from the laser focus point, while the fluid at the bottom of the liquid layer experienced an inward flow toward the beam center [9]. Point, ring, and line indentations have been generated in Fig. 1 (b)–(e) [7].

We used the lubrication theory to model the fluid deformation [10]. The equation in Cartesian coordinates is given by

$$\frac{\partial h}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0, \quad (1)$$

where Q_x and Q_y represent fluxes in the x and y directions, h represents thickness, and t represents time. Solving Eq. (1) will lead to the deformation amount due to the fluxes in both x and y direction. We used a Gaussian intensity distribution for the temperature distribution to match the laser beam profile. The peak temperature is set to be 80°C, which is in consistent with the experiment. The surface tension, viscosity, and density are all temperature and material dependent according to Ref. [10]. The surface tension and gravity lead to the fluid fluxes, which eventually lead to the deformation, corresponding to the change of thickness of the fluid [10]. Figure 1(f) shows the simulated fluid surface deformation driven by the Marangoni effect at different times. The simulation starts at $t = 0$ s, when the Gaussian temperature profile is applied leading to the liquid deformation. The laser beam's center, with the highest temperature, results in the outward flowing of fluid. The outward flowing of the fluid then effectively generates

overflow into the adjacent region. A weak depression is generated at the center, and the deformation valley gets deeper as time evolves. Figure 1(g) shows the overflow height, which is defined as the distance of the peak point above original surface as a function of time. We also show the valley depth, which is defined as the distance of the center valley point below the original surface. According to our simulation, it takes about 2 ms to increase the valley depth to a distance of 0.05 mm, which is consistent with the experimental results [9].

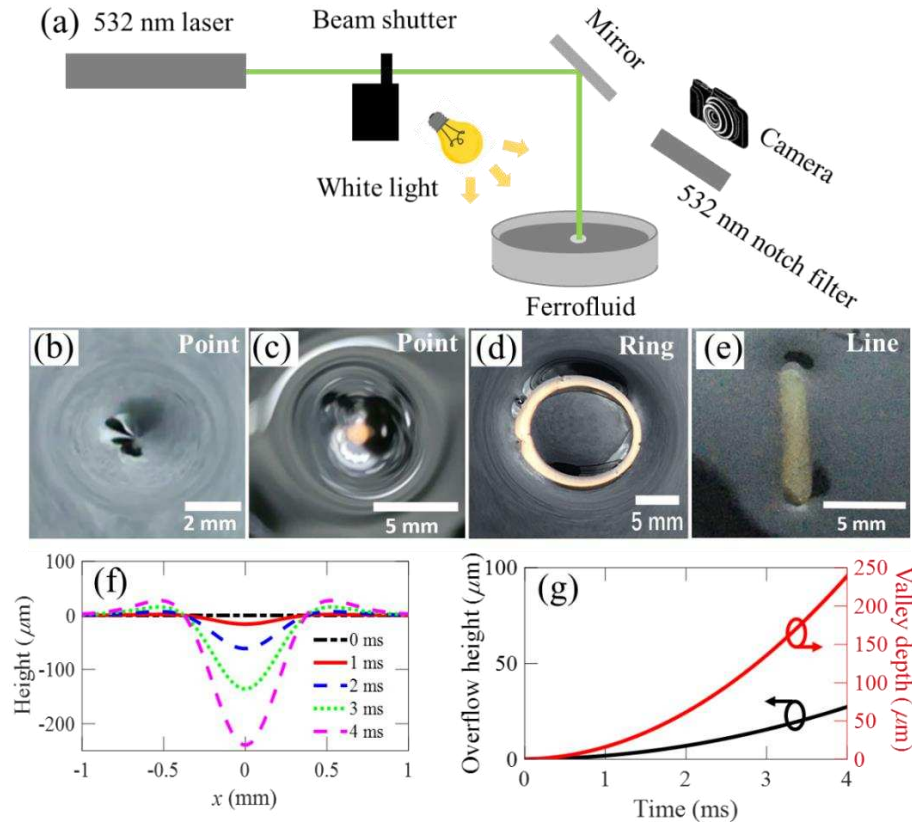


Figure 1(a) Schematic diagram of experimental setup. (b–e) Surface indentations induced by the laser beams. (f) The simulated time evolution of fluid surface deformation. (g) The overflow height and the valley depth as a function of time.

In conclusion, we showed theoretical and experimental results on laser induced liquid deformation with various shapes. Our discoveries, experimental design, and simulation results have enabled us to explore different deformations in thin liquid films. Novel liquids with strong optical absorption can be created by varying the laser wavelength or by adding light-absorbing elements such as colorants or plasmonic nanoparticles.

- [1] G.D. Costa, "Optical visualization of the velocity distribution in a laser-induced thermocapillary liquid flow," *Appl. Opt.* **32**, 2143–2151 (1993).
- [2] G.D. Costa, J. Calatroni, "Self-holograms of laser-induced surface depressions in heavy hydrocarbons," *Appl. Opt.* **17**, 2381–2385 (1978).
- [3] G.D. Costa, J. Calatroni, "Transient deformation of liquid surfaces by laser-induced thermocapillarity," *Appl. Opt.* **18**, 233–235 (1979).
- [4] S.B. Liu, J.C. Liu, J.X. Chen, X.D. Liu, "Influence of surface tension on the molten pool morphology in laser melting," *Int. J. Therm. Sci.* **146**, 106075 (2019).
- [5] F. Laeri, B. Schneeberger, T. Tschudi, "Spatial light modulator based on a deformable oil layer," *Opt. Commun.* **34**, 23–28 (1980).
- [6] J.J. Chen, J. F.-C. Loo, D. P. Wang, Y. Zhang, S.-K. Kong, H.-P. Ho, "Thermal Optofluidics: Principles and Applications," *Adv. Optical Mater.* **8**, 1900829 (2020).
- [7] F. Lin, A.N. Quraishy, T. Tong, R.J. Li, G. Yang, M. Mohebinia, Y. Qiu, T. Vishal, J.Y. Zhao, W. Zhang, H. Zhong, H. Zhang, Z.C. Chen, C.F. Zhou, X. Tong, P. Yu, J. Hu, S.C. Dong, D. Liu, Z.M. Wang, J. R. Schaibley, J.M. Bao, "Marangoni convection-driven laser fountains on free surfaces of liquids," *Mater. Today Phys.* **21**, 100558 (2021).
- [8] R.E. Rosensweig, *Ferrohydrodynamics* (Courier Corporation, 1997).
- [9] F. Lin, A.N. Quraishy, R.J. Li, G. Yang, M. Mohebinia, T. Tong, Y. Qiu, T. Vishal, J.Y. Zhao, W. Zhang, H. Zhong, H. Zhang, C.F. Zhou, X. Tong, P. Yu, J. Hu, S.C. Dong, D. L. Schaibley, J.M. Bao, "Molding, patterning and driving liquids with light," *Mater. Today* **51**, 48–55 (2021).
- [10] H. M. J. M. Wedershoven, C. W. J. Berendsen, J. C. H. Zeegers, and A. A. Darhuber, "Infrared-laser-induced thermocapillary deformation and destabilization of thin liquid films on moving substrates," *Phys. Rev. Applied* **3**, 024005 (2015).