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Imprinting characteristics of droplet lenses on liquid-repelling surfaces into light

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Abstract. We propose an experimental method that allows the investigation of droplets on liquid-repelling surfaces. The described technique goes beyond the standard imaging approaches and reveals a plethora of spatial droplet information, which is usually unavailable. Liquid droplet lenses shape the transmitted light field of a Gaussian laser beam passing though them, thereby forming refracted three-dimensional (3D) light landscapes. We investigate numerically and experimentally these 3D landscapes which are customized depending on the droplet shape as well as its refractive index, and demonstrate the encoding of droplet information. This approach can also be applied for analyzing droplets showing high-speed dynamics, in order to reveal even minimal shape deviations. The developed technique complements and therefor extend the existing conventional tools for the investigation of the droplets formed on liquid-repelling surfaces.

1 Introduction

The investigation of natural liquid-repelling surfaces inspires the invention of novel artificial substrates, which allow frictionless transport of liquids in different systems. A broad field of relevant applications includes self-cleaning, anti-icing phenomena, as well as liquid transport in lab-on-a-chip devices [2]. Thereby, the liquid-repelling effect can have various initial origins, among them are micro- and nano- structuring [3], chemical surface treatment [4], or thermal effects as the Leidenfrost mechanism [5]. For further development of advanced applications as tuneable optoelectronic devices, which enable control over adaptive liquid lenses [6], a deeper understanding of nonwetting behavior is essential.

Standard approaches for the analysis of droplets are based on the two-dimensional (2D) imaging of a volumetric droplet, usually revealing only a fraction of the information on the droplet such as, for instance, the contact angle [7]. When the droplet is illuminated by an expanded coherent laser beam [8], interferometric approach allows for temperature measurements close to the droplet surface. However, this approach does not reveal further properties of the droplet itself.

In this contribution, we propose a method for investigation of liquid droplets on nonwetting surfaces, employing these droplets as thick biconvex liquid lenses[1]. Thereby, the standard 2D imaging is advanced by encoding a plethora of droplet information into the Gaussian laser beam, passing through the liquid lens. The complete 3D shape of the droplet, its tilt with respect to the beam propagation axis, the refractive index, which strongly depends on the liquid and on the temperature, are simultaneously encoded into the transmitted light field.

We experimentally demonstrate the measurement of such a 3D light field, refracted by a water droplet on a natural liquid-repelling surface, a Taro *(Colocasia esculenta)* leaf. Numerical validation of this experiment is realized using a vectorial ray-based diffraction integral (VRBDI) method [9] and is comprehensively described in [1].

2 Experimental investigation of light-shaping features of liquid lenses

For analyzing the 3D light-shaping features of droplet lenses, we design the experimental setup, as shown in Figure 1a. A horizontally polarized Gaussian beam (wavelength $\lambda = 532$ nm) is focused to have the beam waist of $\omega = 450\,\mu$m at the first surface of a droplet resting on a Taro leaf substrate (shown symbolically as a grey plate). The beam waist is chosen to be approximately two times smaller than the droplet dimensions in order to avoid diffraction on the liquid-air surface. The volume of the droplet is controlled by a microfluidic pump. The 3D light field formed by propagation through the droplet is measured in the following way: the refracted beam is imaged by a 20× long working distance microscope objective (MO) and a $f = 200$mm tube lens onto a camera. The MO is mounted on a high-precision translation stage which is controlled by a computer. Within one minute the stage shifts for 1000 µm in 500 steps in z-direction (propagation direction of beam), capturing the transverse intensity distributions for each step. The subsequent longitudinal and

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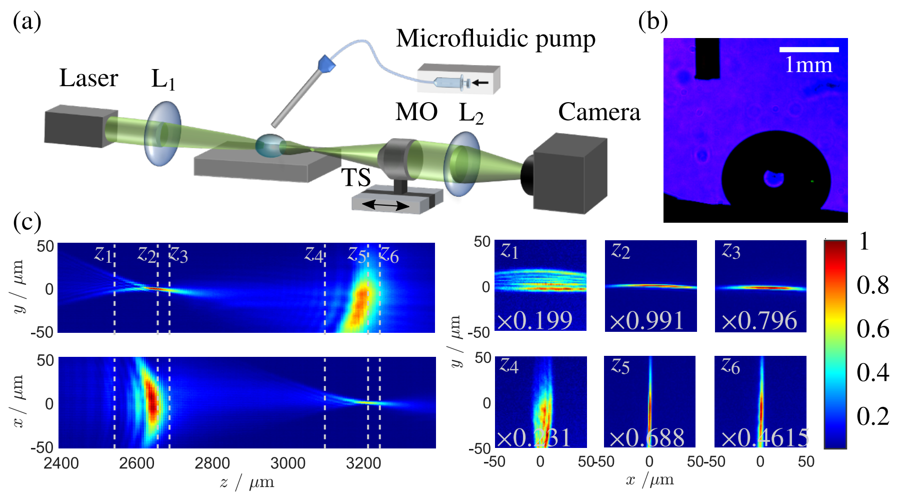

Figure 1. (a) Sketch of the experimental setup used to detect the 3D light landscape refracted by a droplet on a liquid-repelling surface (Taro leaf). A linearly polarized Gaussian beam is focused by the first lens (L_1) into the droplet. The refracted light is imaged by a microscope objective (MO) mounted on a translation stage (TS) and a lens L_2 onto a camera. (b) Droplet on a leaf (camera image, blue LED illumination). A needle (0.4 mm diameter) is shown in the left upper corner. (c) Experimentally measured intensity landscape behind the droplet. $z = 0$ is set to the middle of the droplet. Shown transverse distributions are normalized to the maximum per plane for z-positions z_i = {2550, 2660, 2690, 3100, 3210, 3240} μm, j = [1, 6]. Adapted from [1], licensed under a Creative Commons Attribution 4.0 License.

transversal cuts of the captured light intensity are shown in Fig.1c.

The longitudinal (x, z) and (y, z) cuts demonstrate the presence of strong astigmatism in the optical system, which results in two separated vertical (tangential) and horizontal (sagittal) focal planes. The origin for the astigmatic focusing is the mismatch of the sagittal and tangential curvatures of the light-shaping object, namely, the curvatures of the approximately ellipsoidal droplet in (x,y) and (x,z) planes. This results in different focal distances in orthogonal planes. The corresponding intensity distributions in the transverse planes show the focal structures for different z-positions z_1 to z_6. Intensity fringes before the focal planes are caused by the presence of spherical aberration. Overall, the astigmatic distance is fully defined by the droplet's refractive index and its geometry, allowing conclusions on the liquid-repelling properties of the underlying surface.

3 Conclusion & Discussion

We have introduced a method for the investigation of droplets on liquid-repelling surfaces and present an exemplary experimental measurement of a light landscape sculpted by a water droplet on a Taro leaf. The described approach can also be applied for the imaging of high-speed dynamic movement of droplets, such as a bouncing Leidenfrost droplet on a hot surface [1]. In this case, a minimal displacement of the droplet can hardly be detected by standard imaging techniques, but leads to a significant restructuring of the light landscape. The described method can be extended by using structured laser beams [10] carrying non-zero orbital angular momentum. In this case, it has the potential to also detect further droplet properties, such as internal fluid flows. In total, standard imaging techniques can be complemented by our approach to extract additional information about the droplets and, thereby, the liquid-repelling surfaces they are formed on.

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