Photopyroelectric microfluidics developed by researchers

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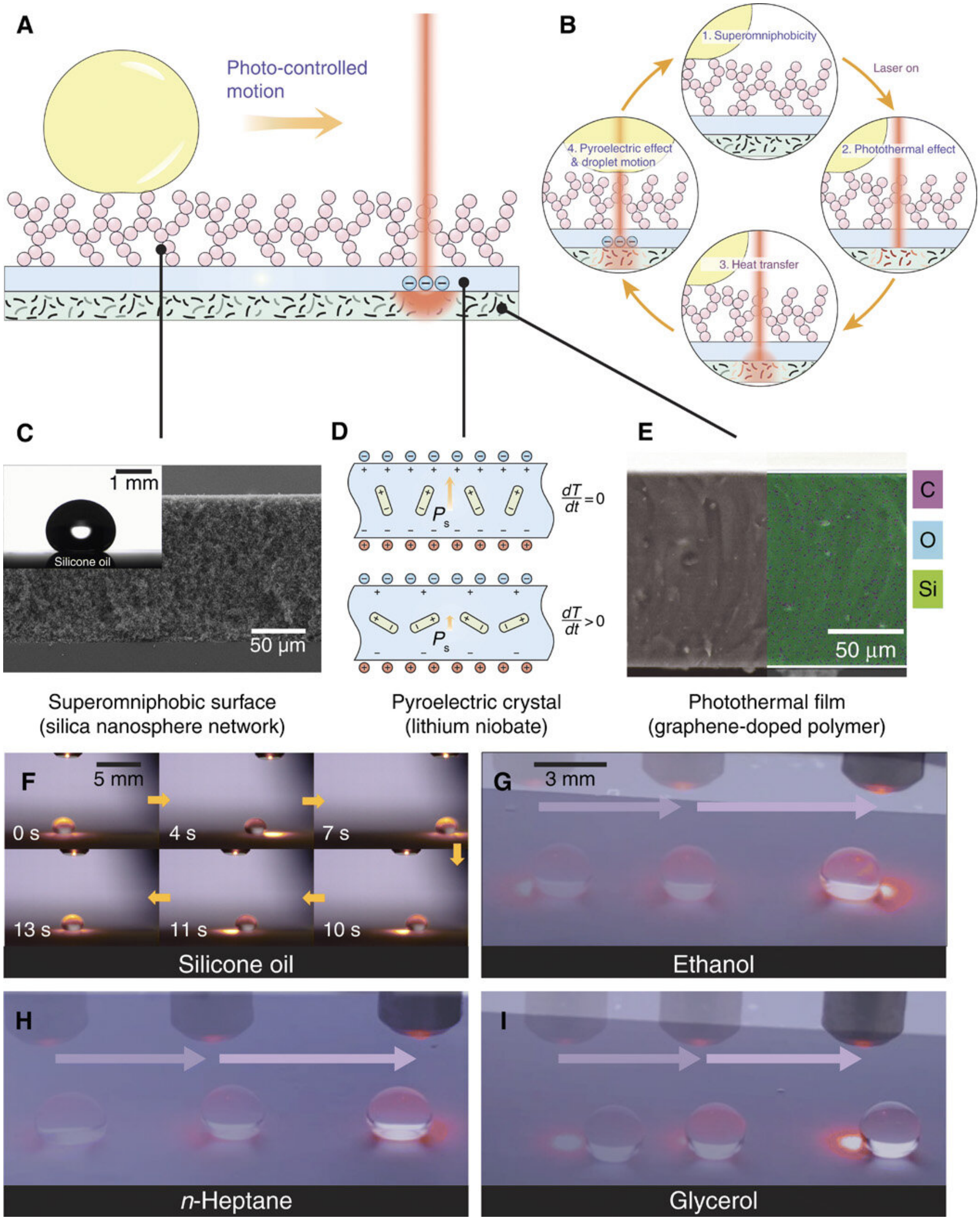
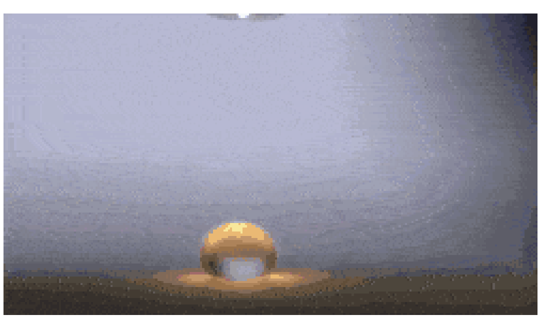


Design of photopyroelectric microfluidics. (A) Schematic of the trilayered photopyroelectric platform consisting of the superomniphobic surface (silica nanosphere network), pyroelectric crystal (lithium niobate), and photothermal film (graphene-doped polymer) where droplets are controlled by a near-infrared (NIR) light. (B) Schematics showing the mechanism of photopyroelectric microfluidics. As light irradiates, the photothermal film composed of graphene nanoplatelets produces heat because of photothermal effect. Through heat transfer, the temperature within the pyroelectric crystal rises, prompting surface free charges, which drives the droplet into motion through dielectrophoretic force. (C) Scanning electron microscopy (SEM) cross-sectional image of the superomniphobic surface. Inset is the image of a 5-μl silicone oil residing on the surface with a contact angle of 151°. (D) As the temperature increases, the spontaneous polarization of pyroelectric crystal decreases, giving rise to extra surface free charges. (E) Cross-sectional SEM and energy-dispersive x-ray spectroscopy images of the graphene-polymer composite film, showing homogeneously dispersed graphene. (F) Sequential images showing a continuous manipulation of a 5-μl silicone oil using a 785-nm laser. Laser is turned on at 0 s, unless otherwise specified. (G) Chronophotographs showing a continuous manipulation of an ethanol droplet. (H) Chronophotographs showing a continuous manipulation of an n-heptane droplet. (I) Chronophotographs showing a continuous manipulation of a glycerol droplet. Photo credit: Wei Li, The University of Hong Kong. Credit: Science Advances, doi: 10.1126/sciadv.abc1693

Precisely manipulating various liquids is essential in many fields and unlike solid objects, fluids are intrinsically divisible. Fluids are also sticky with appropriate functions for lossless manipulation to prevent loss and contamination. In a new report now published on *Science Advances*, Wei Li and colleagues in mechanical engineering and research and innovation in China presented photopyroelectric microfluidics to meet such diverse requirements. The fluidic platform facilitated the development of a unique wavy dielectrophoretic force field from a single beam of light to remarkably perform the desired loss-free manipulation of droplets and function as a "magic" wetting-proof surface. The liquid platform could navigate, fuse, pinch and cleave fluids on demand to establish cargo carriers with droplet wheels and has potential to upgrade the maximum concentration of deliverables such as protein by 4000-fold.

Existing methods to merge fluids

The surface manipulation of buffers and organic solvents is fundamental for many biological applications and chemical functions that are critical for a variety of thermal, optical and medical applications. To accomplish this, scientists must design a platform to enable locally addressable fluids for navigation with a low loss rate to partition and merge in a readily controlled process. Light can outperform other stimuli due to its contactless nature, high precision, and mature ray controllability relative to geometric optics, for example, to form optical tweezers that trap and dislodge micro-objects. Several approaches have therefore explored the potential to photo-manipulate liquids by leveraging the energy conversion of photoelectric, photothermal, photochemical and photomechanical properties to precisely navigate and merge fluids. Nevertheless, these techniques cannot split and manipulate fluids in a loss-free manner. Therefore, in this work, Li et al. presented an unprecedented approach.

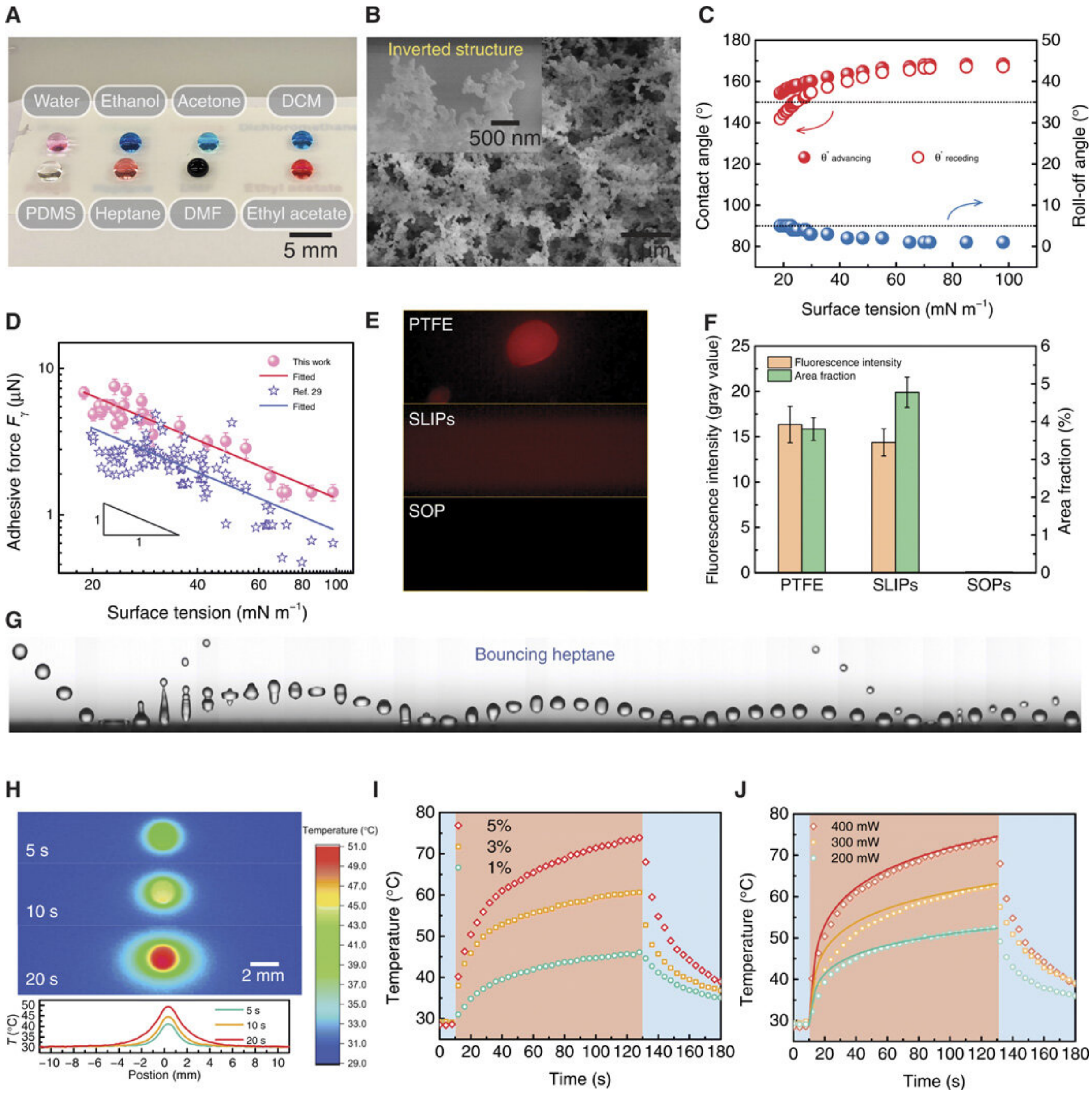


Manipulation of silicone oil, n-hexadecane, n-decane, n-heptane, ethanol, and isopropyl alcohol droplets. Credit: Science Advances, doi: 10.1126/sciadv.abc1693

The new approach

The team simply stacked three homogenous layers, including a photothermal film using a graphene-doped polymer, pyroelectric crystal using a lithium niobate wafer, and a superomniphobic surface using a silica nanosphere. The three layers functioned in concert for loss-free applications of even, ultra-low surface tension fluids in the presence of a single beam of light.

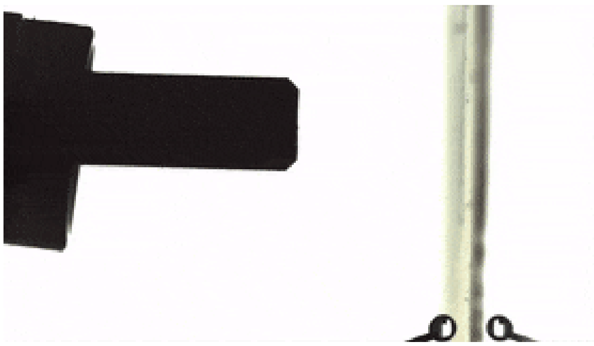
They composed the photothermal film with a graphene monolayer composite to sense the light stimuli and sense the responses generated by uneven thermogenesis. The pyroelectric crystal converted heat into extra electric charges to form a wavy dielectrophoretic force profile that could trap, dispense and split the fluids. They employed the technique to perform four fundamental functions including movement, merging, dispensing and splitting of various liquids under well-controlled, loss-free conditions without complicated electrodes and high-voltage circuits. The approach will have significant impact across multidisciplinary fields.



Characterization of the fluid interfacing and light sensing. (A) Image of droplets of water, ethanol, acetone, dichloromethane (DCM), silicone oil (PDMS), n-heptane, dimethylformamide (DMF), and ethyl acetate residing atop the translucent superomniphobic surface. (B) SEM image showing the fractal network of the superomniphobic surface. Inset shows the typical inverted structures. (C) Super-repellency toward various liquids. (D) Adhesive force is inversely proportional to the surface tension. Error bars denote SD of three independent measurements. (E) Liquid residue detected on diverse omniphobic surfaces by fluorescence imaging. (F) Fluorescence intensity and area fraction of the images in (E), showing the remarkably reduced liquid loss on the superomniphobic (SOP) surface. Error bars denote SD of three independent measurements. (G) Sequential images showing an n-heptane droplet ($r0 \approx 1$ mm, $We \approx 20$) bounces on the surface, exhibiting low adhesion toward organic liquids. Time interval between each snapshot is ~4 ms. (H) Infrared thermal imaging and the plot showing the temperature distribution on photothermal film upon 400-mW laser irradiation. (I) Thermal response of graphene-PDMS composite films with varying contents of graphene nanoplatelets to 400-mW laser irradiation. Blue and red shaded regions denote off and on states, respectively, of the 785-nm laser. (J) Thermal response of PDMS film containing 5 wt % graphene nanoplatelets to laser power. The solid lines are from theoretical analysis. Photo credit: Wei Li, The University of Hong Kong. Credit: Science Advances, doi: 10.1126/sciadv.abc1693

Designing photopyroelectric microfluidics

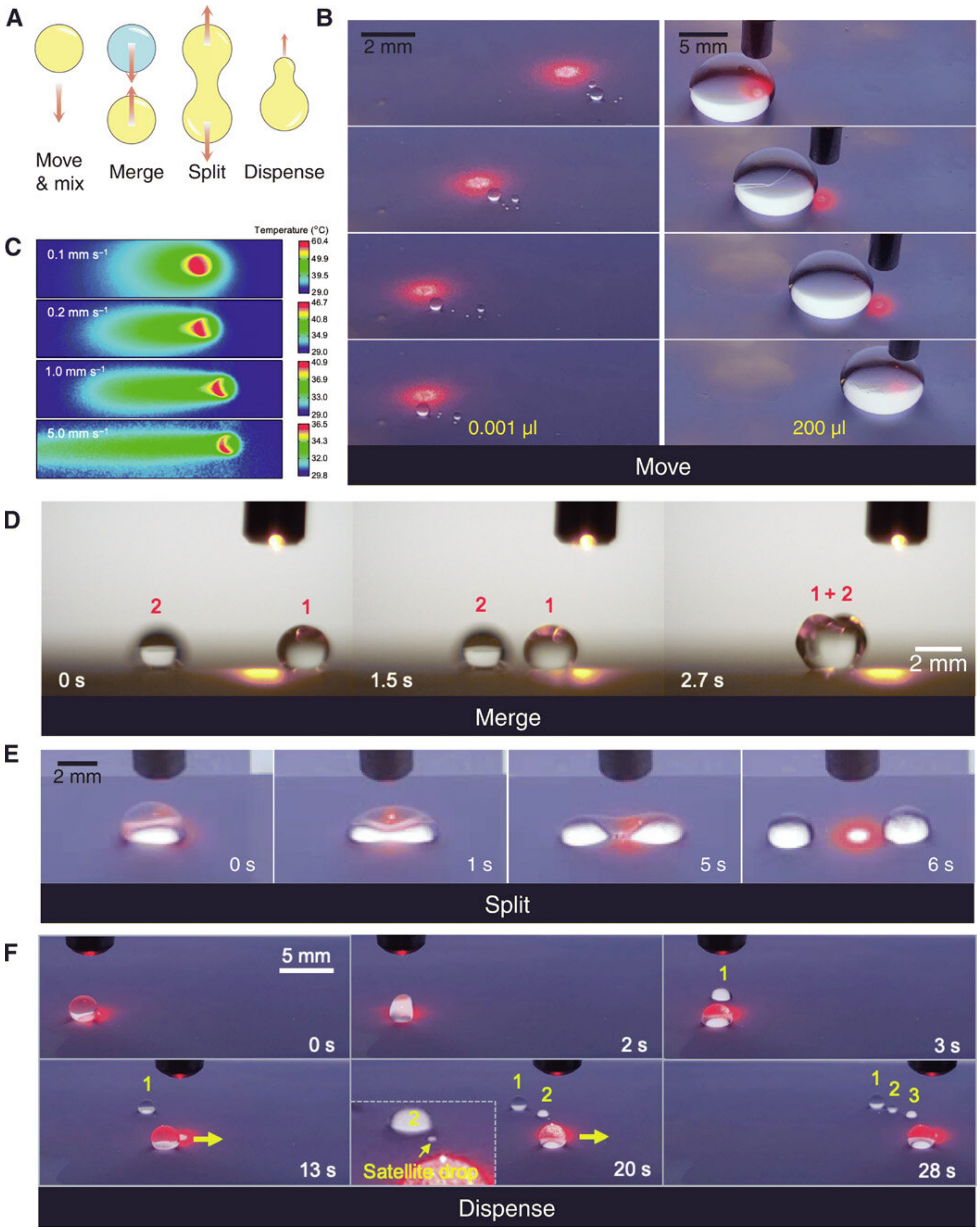
Li and team used the three layers of closely sandwiched materials (the pyroelectric crystal, superomniphobic thin film and photothermal thin film) to form the platform. The top superomniphobic layer contained nanoscale fractal networks made by sintering hollow silica spheres covered with fluorinated surfactants to achieve super-repellence. In the bottom layer, they formed a uniform composite film by homogenizing graphene nanoplatelets with polydimethylsiloxane (PDMS) and cured the polymer. When a beam of near-infrared (NIR) light irradiated the surface, the translucent superomniphobic surface and pyroelectric wafer became a transparent window allowing the NIR to readily reach the underlying composite polymer film. This led to a partially uneven, localized temperature rise, giving form to extra surface free charges, allowing droplets on the superomniphobic surface to be driven forward to the irradiated spot via a dielectric force. The scientists applied the technique to a variety of liquids including organic solvents such as silicone oil, alkanes and alcohols. The platform provided a channel-free, open-space fluidic processor without the hassle of electrodes or micropatterning required for currently existing microfluidic counterparts.



Droplet climbs vertical wall. Credit: Science Advances, doi: 10.1126/sciadv.abc1693

Loss-free fluid interfacing, light sensitive sensing, and droplet dynamics

The superomniphobic surface was chemically resistant to corrosive acids and bases, allowing a stable cassie state to remain on the surface for chemical fluidic processing. The scientists confirmed loss-free fluid interfacing via fluorescence imaging of the omniphobic surface and compared the results with controls to show near loss-free contact with fluids on the material of interest. Li et al. thereafter noted the light-sensing capacity of the system to show the conversion of irradiated light into a sharply bulged temperature profile in the system. They then investigated the motion of a 5 microliter (μl) droplet of water placed 13 mm away from the light spot center. When they turned the laser on, the droplet was attracted to the illumination in an oscillating mode, where it initially accelerated toward the laser, then rapidly braked and reversed direction on reaching the light spot's edge. To understand the underlying physics of droplet dynamics, the team developed a numerical simulation and varied the liquid types for the calculations to show that higher the relative permittivity and surface tension, the easier for liquid motion.



Fluidic operations. (A) Schematics showing four fundamental fluidic operations, including navigate, merge, split, and dispense. (B) Guided motions of a 0.001-µl silicone oil and 200-μl water droplets, showing the broad controllable volume range. (C) Infrared thermal imaging showing the temperature distribution within pyroelectric crystal along the direction of moving laser spot. (D) Sequential images showing the merge between two isolated water droplets. (E) Sequential images showing the split of an ethanol droplet upon a centered prolonged irradiation. Laser is turned on at ~−2 s. (F) Sequential images showing the dispenses of liquid portions from a silicone oil droplet through offset prolonged irradiation. Photo credit: Wei Li, The University of Hong Kong. Credit: Science Advances, doi: 10.1126/sciadv.abc1693

Fluidic functionality, versatility, and biocompatibility

The team performed a variety of fluidic functions using a single beam of laser light, where the wavy dielectrophoretic force profile could unexpectedly trap and move droplets with a volume as low as 0.001 μL. The team also handled a 200 μL puddle without loss on the platform, suited for miniaturization of biomedical systems. However, the technique had its limits with a maximum laser-moving velocity beyond which the droplet could not keep up with laser movement. Additionally, Li et al. facilitated a strong navigating force for droplets to defy gravity and ascend uphill by placing the platform vertically, allowing the superior technique to precisely manipulate various liquids at the micro-/nanoliter scale, which is of fundamental importance across multiple fields. Using the method, the team observed the loss-free detection of amino acids such as glycine and low-surface tension liquids such as ethanol. The method has great potential in analytical chemistry, medical diagnosis, and biomedicine.

In this way, Wei Li and colleagues developed a unique wavy dielectrophoretic force field in response to light stimuli with a three-layered surface for well-controlled, loss-free liquid motion, merging, dispensing and splitting functionalities. They readily modified the force by superimposing multiple light irradiations for richer fluidic functionality and droplet patterning applications. The method will facilitate fluid maneuver on demand for applications in biochemical and fluidic processing reactions, fluidic engineering and manufacturing for precision patterning and for droplet multi-compartmentalization.

More information: Wei Li et al. Photopyroelectric microfluidics, *Science Advances* (2020). DOI: 10.1126/sciadv.abc1693

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