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Short communication

# Self-driven flow in surface grooves fabricated by femtosecond laser

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ABSTRACT

The self-driven flow in microfluidic devices has attracted much attention due to its efficient, fast and convenient properties. We investigated the effect of femtosecond laser pulse overlap on the liquid flow characters in surface grooves both in experimental evidence and theoretical analysis. With the increase of the femtosecond laser pulse overlap, the speed of water flowing in grooves is increased. Both the surface granular protrusions microstructures and the surface chemical composition can influence the liquid dynamics in grooves. Femtosecond laser may have potential applications in self-driven microfluidic devices.



## 1. Introduction

Microfluidic devices have attracted much attention because they have many applications in medical analysis, environmental monitoring, biochemical analysis, and microchemistry [1,2]. Accurate control of the flow of liquids in microfluidics is key to their proper functioning [3]. Actuated microfluidics [4–6] and passive microfluidics [7,8] are two modes which can drive fluid to flow in microfluidic devices. Capillary-driven flow is one of the simplest approaches to driving flow in microfluidics. With the miniaturization of the microfluidic devices, self-driven microfluidic devices have many advantages due to its portability, low volume and small power consumption. Capillary-driven microfluidics have been used in chemical/biochemical analysis and clinical diagnostics [9,10]. Water kinetics in self-driven microgrooves is determined by the geometry features of the grooves, the liquid properties and the contact angle. It's known that the contact angle of a rough surface is determined by its chemistry and morphology. In recent years, laser surface structuring has been used to alter solid surface wetting properties in air [11,12]. The microgrooves with different widths and surface energy induced by nanosecond laser in air were studied [13]. We want to tackle the effects of the surface morphology and the surface chemical composition on liquid dynamics in surface grooves. Here, we used femtosecond laser to produce self-driven surface grooves on aluminum surfaces in air and studied water flow characters in them. We conducted this study to determine whether different femtosecond laser pulse overlaps can influence the dynamics of the liquid in surface grooves. We investigated the change of the microstructures and chemical composition of the aluminum surfaces grooves after femtosecond laser irradiation. Moreover, we analyzed the influence of surface microstructures and the surface chemical composition on the liquid dynamics in surface grooves. It is meaningful for microfluidic devices to fabricate self-driven surface grooves on samples by using femtosecond laser.

## 2. Experimental section

Schematic illustration of the experimental system is shown in Fig. 1. We used an amplified Ti: sapphire laser system to process aluminum surface and studied the liquid dynamics on the treated surface grooves. The system generates the pulse duration of 120 fs at a maximum repetition rate of 1 kHz. The laser beam has the central wavelength of 800 nm. The combination of a $\lambda/2$ wave plate and a Glan–Taylor polarizer is used to vary the pulse energy. Lens A and Lens B make up the shrink-beam system. In the fabrication, the laser beam position was controlled by the Galvo Scanning System (Scanlab hurrySCANII) commanded by a computer. High-purity (99.99%) aluminum slides (GRINM) with a dimension of $30 \times 10 \times 0.3$ mm$^3$ were used in our experiments. Before the femtosecond laser irradiation, the aluminum samples were degreased in acetone and ethanol. And then the samples were washed in deionized water and air dried. The laser beam with an average fluence of 318.3 J/cm$^2$ was horizontally polarized and focused normally on the samples which were mounted horizontally on a stage. The diameter of the focal spot was about 20 μm which was focused by a focusing lens with 50 mm focal length. The laser scanning velocities were set as 1 mm/s, 5 mm/s, 9 mm/s and the corresponding pulse overlaps were 0.95, 0.75, and 0.55. By scanning the laser beam over the sample, a 20-mm-long microgroove along the x-direction was produced. After a y-direction shift of the laser position by 20 μm we produced the next microgroove and the process was repeated to create an irradiated area of $20 \times 2$ mm$^2$. All the samples were fabricated in air of atmospheric pressure.

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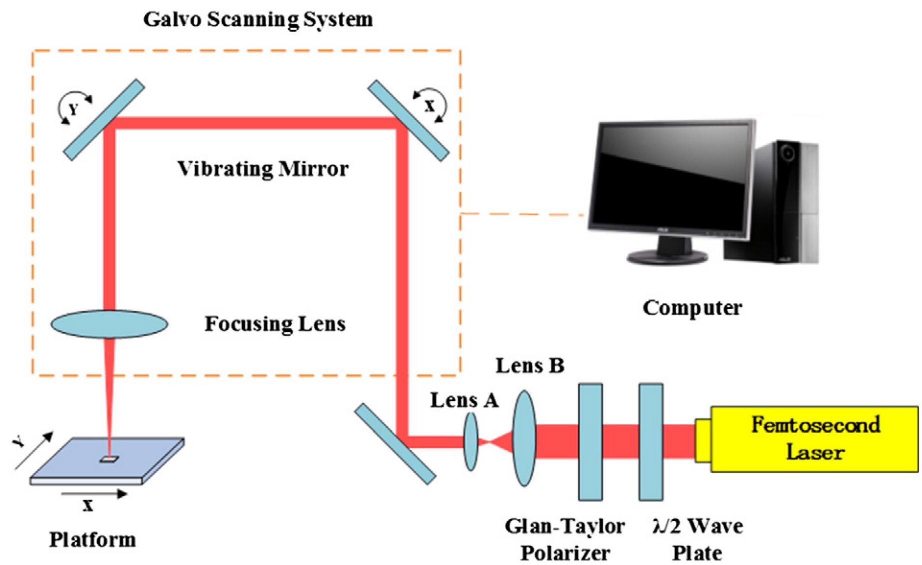


**Fig. 1.** Schematic illustration of the femtosecond laser experimental system.

## 3. Results and discussions

We studied the manufactured aluminum surface grooves wetting properties by examining the spreading dynamics of liquid on the produced samples. Deionized water was used in our study, and we captured the close-up video of the capillary rise of liquids over the aluminum surface grooves by using a 30 fps Sony digital camera. Fig. 2 shows that the water spreads highly anisotropically on the treated area and flows preferentially along the modified area fabricated at 75% pulse overlap. It can be observed that the water spreading speed decreases with time and the water can rise several centimeters on the textured sample. The results we obtained demonstrate that the produced aluminum surface grooves become superhydrophilic. We believe that self-driven flow phenomenon is due to the supercapillary effect [12].

Treatments of the kinetics of capillary flow have been studied for over 90 years. In 1921, Washburn showed that the length of liquid column $z$, entering the horizontal cylindrical capillary followed relatively simple kinetics $z(t) = [\gamma r \cos\theta/(2\mu)]^{1/2}t^{1/2}$ [14]. $z$ is the distance traveled by the liquid, $\theta$ is the contact angle, $r$ is the capillary radius, $\gamma$ and $\mu$ are the surface tension and viscosity of liquid. The equation shows that capillary-driven liquid advances with a $t^{1/2}$ dependence. The flow of liquid on a surface with open V-shaped grooves has been reported by Rey and Yost et al. in 1996. They reported that for horizontally placed capillary flow, experiment and a model agree on kinetics of the form $z(t) = [K(\alpha,\theta)h_0\gamma/\mu]^{1/2}t^{1/2}$ [15–17]. $h_0$ is the groove height, and $K(\alpha, \theta)$ is a geometric term containing the groove angle $\alpha$ and the contact angle $\theta$, $\gamma$ and $\mu$ are the liquid surface tension and viscosity. The dynamics of liquid on the structured surface is purely capillarity driven and depends on the contact angle, the surface tension and viscosity of the liquid, and the geometry of the groove [9,18]. For the purpose of simplicity of the penetration, the surface roughness is assumed to be composed of an array of well-defined pillars [19], channels [20] or a network of grooves [21]. The analytical model established in their studies recovered the Washburn-type kinetics for the early stage of the spreading process. Hemiwicking is a term employed by Quéré to categorize nearly all dynamic wetting across textured surfaces [22]. As he emphasized, a well-controlled micro/nanostructures on a solid may induce roughness effects on wetting. They summarized the dynamic law of the capillarity on textured surfaces as $z(t) = (Dt)^{1/2}$. $D$ is the coefficient which can characterize the dynamics.

In order to determine whether the laser pulse overlap can influence the groove penetration coefficient, we used different pulse overlaps to fabricate surface grooves. To determine the diffusion dynamics of the femtosecond laser-structured surface grooves, we plotted the uphill travel distance $z$ as a function of $t^{1/2}$ for the vertically standing sample fabricated at different laser pulse overlaps, as shown in Fig. 3. The penetration distance is directly proportional to the square root of the associated time. The slope of the line at high pulse overlap is higher than that at low pulse overlap. The slopes of the fitting lines are 5.3, 4.2 and 3.6. And the corresponding dynamic coefficients are 28.09 $mm^2/s$, 17.64 $mm^2/s$ and 12.96 $mm^2/s$. The theoretical model fits the experimental data well. We can change the sample dynamic coefficient by varying femtosecond laser pulse overlap. Therefore, we can control the dynamic properties of the liquid in aluminum surface grooves.

The driving force for capillarity is surface tension, so it is also known as surface tension effects. The occurrence of capillarity requires a good wetting condition between liquid and solid [23]. Wetting of a solid surface is studied for many years [20,22,24]. It's known that the wettability

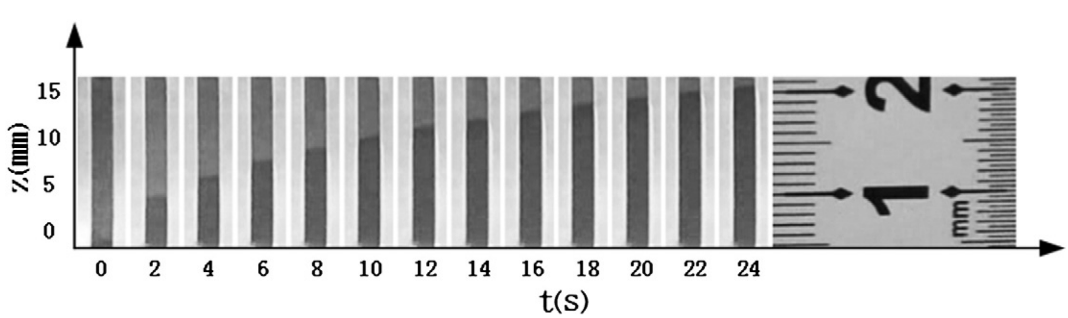


**Fig. 2.** Image sequence of capillary rise fronts of water wicking over an aluminum surface groove.