ELECTRO-ELASTO-CAPILLARITY: ELECTRIC FIELD DRIVEN UNWRAPPING OF WATER DROP WITH ELASTIC FILM

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Summary Electro-elasto-capillarity (EEC) is a new method for droplet encapsulation controlled by electric field. Here we report, for the first time, EEC is realized in experiments, which is also an electrowetting progress on moving substrate. Under the combined effect of surface tension, elastic force and Coulomb force, the flexible thin film can encapsulate and release a tiny droplet, controllably and reversibly. When the voltage reaches a critical value, the film is pulled-in to the substrate and release the droplet. When applied with AC voltage, the droplet vibrates in the frequency of the twice of the frequency of the input electric field. A theoretical model was established to describe the frequency doubling phenomenon and it was found that the theoretical data show good agreement with the experimental results. Our finding may offer a practical method for drug encapsulation and microfluidic devices actuation.

INTRODUCTION

Small objects are usually more difficult to be controlled compared with normal size objects; just like we can hardly find a proper container for a one micro litre droplet (the diameter is no larger than 1 mm) [1]. Elasto-capillarity (EC), also named as capillary origami, is one convenient method to encapsulate a sessile droplet by the help of surface tension [2-4]. Under the driving of capillary force, elastic film will wrap a droplet when the size of droplet is getting larger than a characteristic length L_{EC} , spontaneously. L_{EC} is expressed as

$$L_{EC} = \sqrt{\frac{D}{(1+\cos\theta)\gamma}} \tag{1}$$

where D, γ and θ are the bending stiffness of the film, surface tension of the droplet and contact angle of film, respectively. This characteristic length shows the competition between elastic force of thin film and surface tension of droplet.

However, EC is not a practical method to controllably and reversibly manipulate the droplet. By inducing electric field into the droplet, the encapsulation and release procedure can be realized and we call it electro-elasto-capillarity (EEC). EEC offers a novel method for micro-scale actuation and self-assembles of moveable devices. It also provides a good candidate for the drug delivery at micro- or nanoscale [5-7].

EXPERIMENTS

In the experiment, tiny salty droplet is placed on the surface of a flexible thin (70 μm thick) polydimethylsiloxane (PDMS) film (Fig. 1). As the result of the vertical component of liquid-vapor interface tension, the thin film was bent upward and wrapped the droplet when the size of drop is larger than L_{EC}. The PDMS film was laid down on superhydrophobic surface to minimize the adhesion force of the substrate and to provide a dielectric surface. For this system L_{EC} = 0.44 mm, consequently, when the droplet touches the thin film, the film will wrap the droplet.

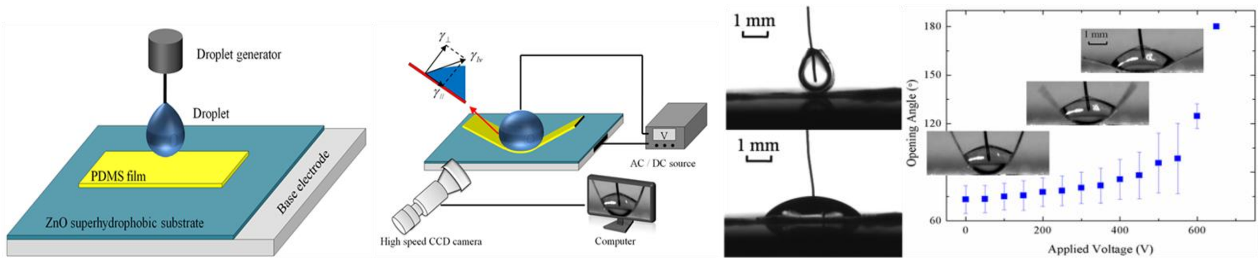

Fig. 1 Schematics of the experimental setup and the experimental results of EEC.

After the droplet was wrapped completely by the film, one Pt wire electrode was inserted into the droplet from the top. The other electrode was set beneath the superhydrophobic substrate. Then, electric field will be formed through the droplet and the thin film when both of the electrodes are connected to the electric source. The liquid used in the experiments is 0.1 mol/L KCl solution, which provides a slightly higher surface tension than pure water and a better electric conductivity. The entire procedure of EEC was captured by DataPhysics OCA-20 contact angle meter and a 1000 fps (frames per second), 640 * 480 pixels (resolution) CCD camera. The PDMS film used in the experiments is prepared by spin coating process under 1000 rpm (revolutions per minute) [8-9] and then cut into 5 mm * 1 mm rectangular slices.

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In EEC, when applied with electric field, the PDMS film tends to unwrap the drop because of the joint effect of Coulomb force, surface tension and elastic force (Fig. 1). When the voltage reaches a critical value, about 650 V in this experiment, the film is pulled-in to the substrate and release the droplet completely.

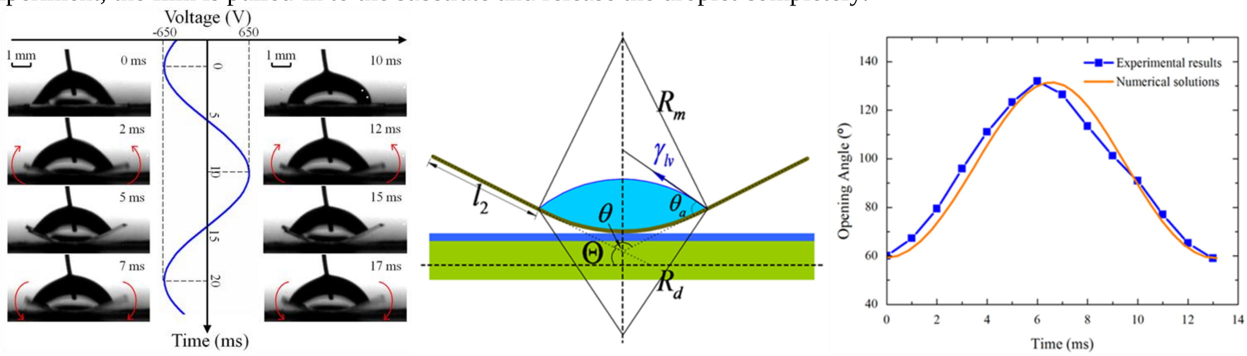

Fig. 2 Frequency-doubling phenomenon and theoretical model for EEC

Since the process of EEC is reversible, we applied AC electric field on the droplet. We find that the droplet start to vibrate. We analyzed the vibration of frequency and found that the vibration frequency is twice of the frequency of electric field. The procedure of vibration is shown in Fig. 2.

THEORETICAL ANALYSIS

The Lagrangian equation for this system with damping can be written as

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\Theta}} - \frac{\partial L}{\partial \Theta} + \frac{\partial D}{\partial \dot{\Theta}} = 0, \tag{2}$$

where $L = E_k - E_b - E_s - E_e$ is the Lagrangian.

Then, the governing equation for the vibration of the lateral PDMS wings can be derived by using Eq. (2)

$$2I\frac{d^2\Theta}{dt^2} = -\frac{4Bw\Theta}{l_1} - \frac{\gamma_{lv} w l_1 \Delta}{\sin\Delta}\frac{\Theta\cos\Theta - \sin\Theta}{\Theta^2} - \frac{\pi\varepsilon w\sqrt{l_1/h'}V_0^2\sin^2\omega t}{4\Theta^{3/2}} - C\frac{d\Theta}{dt} \tag{3}$$

The numerical solution of Eq. (3) was shown in Fig. 2, under the initial conditions $\Theta(t=0)=\pi/3$ and $\Theta_t(t=0)=0$, which were estimated from the experimental data. From Figure 5 (b), we can see that our theoretical model captures the frequency doubling of the AC voltage induced vibration, which indicates that the electric energy term consist of $\sin^2\omega t$ may be dominant in the governing equation. Also we can see that the theoretical data show good agreement with the experimental results.

CONCLUSIONS

For the first time, EEC is realized in experiments, which can also be considered as a paradigm shift for electrowetting from rigid substrate to moving substrate. Actuated by Coulomb force and surface tension, the encapsulated water droplet can be released, controllably and reversibly. When applied with AC voltage, the droplet vibrates in the frequency of the twice of the frequency of the input electric field. A theoretical model was established. This controllable and reversible method of unwrapping of droplet will offer a possible way of drug encapsulation and microfluidic device actuation.

Acknowledgements

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