Spectral tuning of liquid microdroplets standing on a superhydrophobic surface using electrowetting

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Using electrowetting, we demonstrate reversible spectral tuning of the whispering gallery modes of glycerol/water microdroplets standing on a superhydrophobic surface by up to 4.7 nm at 400 V. Our results can inspire electrically tunable optical switches and filters based on microdroplets on a superhydrophobic surface. The sensitivity of the observed spectral drift to the contact angle can also be used to measure the contact angles of microdroplets on a superhydrophobic surface. © 2008 American Institute of Physics. [DOI: 10.1063/1.2927373]

Optical communication systems require largely tunable optical microcavities to function as building blocks of largely tunable optical switches and filters.1 Liquid microdroplets standing on a superhydrophobic surface possess unique features which can make them technologically favorable in such applications. First, due to their liquid nature, these microdroplets are easily deformable.2,3 Second, thanks to the superhydrophobic surface, their position stabilization is granted. They do not require complex position stabilization techniques such as electrodynamic levitation4 or optical tweezing.5 Third, they are cost effective and disposable. They do not pose any microfabrication challenges. Fourth, the interaction of these microdroplets with the superhydrophobic surface inspires unique shape deformation mechanisms. To this end, here we demonstrate spectral tuning using electrowetting.

Electrowetting is the increase in the wetting of a superhydrophobic surface by conducting liquid microdroplets due to an external electric field.6 As a result of an applied voltage, a space charge layer of counter ions is built near the superhydrophobic surface in the microdroplet. This leads to a decrease in the effective solid-liquid interfacial tension which in turn decreases the contact angle. Electrowetting has recently become a powerful tool in microfluidics research inspiring various important applications including lab-on-a-chip devices in which microdroplets are translated along arbitrary paths,7 adjustable microlenses,8 and electronic displays.9 In this letter, we report the spectral tuning of the whispering gallery modes (WGMs) of glycerol/water microdroplets standing on a superhydrophobic surface using electrowetting. The decrease in the contact angle leads to an increase in the equatorial radius of the microdroplets resulting in the redshift of the WGMs which circulate in the equatorial plane parallel to the surface. We demonstrate spectral tuning by up to 4.7 nm as a result of a maximum applied voltage of 400 V. We also show that the observed spectral tuning mechanism is reversible.

The sketch of the experimental setup is shown in Fig. 1. Two cover glasses having conducting, indium tin oxide (ITO) coatings on one of their surfaces were used in the sample chamber. The nonconductive surface of one of the cover glasses was spin coated with hydrophobically coated silica nanoparticles (Degussa AG, LE2) using a 50 mg/ml ethanol dispersion. Glycerol/water microdroplets were sprayed onto the superhydrophobic surface using an ultrasonic nebulizer from a 10/90 glycerol/water solution containing 5 μM rhodamine B and 135 mM KCl. Water content in the microdroplets quickly evaporated on the superhydrophobic surface under ambient temperature and pressure and a relative humidity of 40%, revealing microdroplet diameters ranging from a few up to 20 μm with resulting glycerol contents >90%. Following microdroplet generation, the second cover glass was glued on the first cover glass with its ITO coated surface facing the superhydrophobic surface. The spacing between the two cover glasses was kept at minimum by squeezing during the sealing of the chamber. After the adhesive was hardened, spacings of d1=30–60 μm were typically obtained, and the chamber between two cover glasses was totally sealed. All the data presented in this letter were taken from microdroplets in the same sample chamber with a spacing of d1=40 μm. In all results presented, a positive voltage was applied between nodes A and B, (VAB ≥ 0). Similar spectral shifts in the WGMs were observed as a function of VAB for all microdroplets when the sign of VAB was reversed. Spectral positions of the WGMs were determined with fluorescence spectroscopy experiments. Individual microdroplets were excited in the vicinity of their rims with a green, solid state laser (λ=532 nm) using an air objective

FIG. 1. (Color online) Illustration of the experimental setup. C, cover glass; S, superhydrophobic coating; ITO, indium tin oxide coating; O, microscope objective. The sketch is not to scale. c1 and c2 indicate capacitances per unit area.

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In this equation, $\theta$, $\epsilon_0$, $\epsilon_d$, $\sigma_{in}$, and $d$ denote the Young’s equilibrium contact angle, permittivity of free space, dielectric constant of the insulating layer, liquid-vapor interfacial energy, and the thickness of the insulating layer, respectively. In our experimental configuration, the voltage is not directly applied between the microdroplet and the conducting layer. Applied voltage ($V_{AB}$) and the actual potential difference between the microdroplet and the conducting layer underneath ($U$) are related as $U=V_{AB}c_\text{eq}/c_2$, where $c_1$ and $c_2$ (shown in Fig. 1) denote capacitances per unit area, and $c_\text{eq}=c_1c_2/(c_1+c_2)$ is the equivalent capacitance per unit area.

In Fig. 2 we plot the dependence of the equatorial radius ($r$, normalized to 1 for the ideal sphere) of an ideal truncated sphere to $\cos \theta$ considering that the volume is kept constant. A linear approximation to this curve can be made assuming small changes in the contact angle. Furthermore, for large mode numbers, a linear asymptotic relationship exists between the spectral position of the WGMs ($\lambda$) and $r$. As a result, a parabolic relationship can be expected between $\lambda$ and $V_{AB}$, for small changes in the contact angle. Assuming an unbiased (under 0 V) contact angle of 150°, the following relationship is obtained:

$$\cos \theta = \cos \theta_0 + \frac{e_0 \epsilon_d U^2}{2d \sigma_{in}}.$$

In this equation, $\theta$, $\epsilon_0$, $\epsilon_d$, $\sigma_{in}$, and $d$ denote the Young’s equilibrium contact angle, permittivity of free space, dielectric constant of the insulating layer, liquid-vapor interfacial energy, and the thickness of the insulating layer, respectively. In our experimental configuration, the voltage is not directly applied between the microdroplet and the conducting layer. Applied voltage ($V_{AB}$) and the actual potential difference between the microdroplet and the conducting layer underneath ($U$) are related as $U=V_{AB}c_\text{eq}/c_2$, where $c_1$ and $c_2$ (shown in Fig. 1) denote capacitances per unit area, and $c_\text{eq}=c_1c_2/(c_1+c_2)$ is the equivalent capacitance per unit area.

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changes assumption in the contact angle and deviation of the unbiased contact angle from 150°. Reversibility of the spectral tuning mechanism is also demonstrated in Fig. 4(a). As $V_{AB}$ is decreased from 400 to 0 V, no hysteresis is observed in the spectral position of the WGM A. Figure 4(b) shows the plots of spectral drift versus $V_{AB}$ for eight microdroplets located in the same sample chamber, including the microdroplet discussed in Figs. 3 and 4(a) (microdroplet A). Parabolic relationships are observed in all the microdroplets with parabolic coefficients ranging from $1.56 \times 10^{-5}$ nm/V$^2$ for microdroplet H to $2.94 \times 10^{-5}$ nm/V$^2$ for microdroplet G. At 400 V, a maximum spectral drift of 4.7 nm is observed in microdroplet G. The difference in the observed parabolic coefficients of the microdroplets can be attributed to different unbiased contact angles within an estimated range of 135° (microdroplet G)–150° (microdroplet H).

We have demonstrated a reversible electrical tuning mechanism to tune the WGMs of glycerol/water microdroplets by up to 4.7 nm at 400 V. Our results can inspire electrically tunable devices for optical communication systems based on glycerol/water microdroplets standing on a superhydrophobic surface. The use of larger diameter microdroplets can be important for future implementations, especially because of the independence of the spectral drift at a certain applied voltage from the value of the equatorial radius. In such studies, selective excitation of the high quality WGMs circulating in the equatorial plane can be achieved using fiber coupling. Finally, because of the strong dependence of the parabolic coefficient to the unbiased contact angle, the presented method can be used in measuring the contact angles of microdroplets with a high accuracy.

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