Optical Engineering

RESEARCH PAPER

Reduction in the interfacial tension between liquids for the low-voltage control of electrowetting cylindrical lenses

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ABSTRACT. A method to reduce the control voltage of an electrowetting double-liquid cylindrical lens was introduced and validated. We added a lower-surface-tension liquid to the original conductive liquid to reduce the interfacial tension between the two liquids and thereby reduce the control voltage. The control voltage of the electrowetting cylindrical lens could be significantly reduced using this method while ensuring the zoom range, as the initial curvature of the liquid interface and the refractive index difference between the two liquids changed little. Both the theoretical and experimental results helped prove the above conclusion. The surfactant was found to be the best low-surface-tension liquid, as it could reduce the control voltage by 47% as the focal length tended to infinity. Our study results can serve as a basis for the development of zoom lenses.

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1 Introduction

A zoom lens is a common type of optical device widely used in the design of imaging optical systems.[1–3] Zoom lenses can be prepared using two common methods. The first method is a conventional one, where the zoom effect is achieved by changing the distance between glass lenses.[4–6] The other method is changing the properties of the liquid to achieve the zoom effect. For example, in a liquid-filled lens,[7,8] the focal length is varied by changing the type or volume of the liquid, and in an electrowetting lens,[9–11] the focal length is varied by changing the applied voltage to control the liquid surface curvature. The conventional zoom method requires many mechanical structures, which can be difficult to integrate. In the case of a liquid-filled zoom lens, it is time-consuming to change the liquid type or volume.[12] By contrast, an electrowetting lens has a more rapid response and a more compact structure,[13] with broad application prospects, particularly the double-liquid lens. However, the control voltage, which is related to the properties of the dielectric layer and liquids used, is high, and it is an important factor limiting the application of electrowetting lenses. Generally, the control voltage is reduced either by selecting a thinner dielectric layer or by lowering the interfacial tension of the liquid/liquid components.

In Ref. 14, the voltage applied to an electrowetting lens at an infinite focal length could be reduced to 75 V by reducing the thickness of the dielectric layer of the lens down to 3.6 μm. However, at lower thicknesses, the dielectric layer becomes more vulnerable to breakdown in the

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experiment, and the electrolytic voltage of the electrowetting lens decreases,[15] leading to a significantly narrower zoom range of the electrowetting lens, contrary to the design intent. In addition to reducing the thickness of the dielectric layer, the type of liquid was changed,[16] i.e., the conductive liquid in the electrowetting lens was replaced by an ionic liquid with a lower surface tension; this helped reduce the control voltage of the electrowetting lens to ∼65 V. However, the refractive index of the ionic liquid is close to that of the nonconductive oil encapsulated in the ionic liquid; therefore, the refractive effect of the ionic liquid electrowetting lens is not satisfactory in the actual optical path. Therefore, a salt solution, rather than an ionic liquid, is used more frequently in the design of general imaging optical path.

The problem of reducing the interfacial tension between the two liquids in the lens with a high refractive index difference must be resolved. The above method has been used to reduce the control voltage of droplets, producing some good results.[17,18] However, few studies have proved whether this method is effective for an electrowetting lens, which has a larger volume than a droplet.

In our previous work,[19] a focus-tunable electrowetting liquid cylindrical lens, which is useful for beam steering but remains relatively unexplored, was designed and fabricated; however, it had the same problem of control voltage. In this study, we reduced the interfacial tension between the two liquids in the lens by mixing a lower-surface-tension, low-refractive-index liquid with a salt solution, thereby reducing the control voltage of the electrowetting cylindrical lens while ensuring its zoom range. This method is also applicable to electrowetting liquid spherical lenses.

2 Working Principle of Electrowetting Cylindrical Lens

A cuboid cavity, shown in Fig. 1(a), filled with two liquids can serve as an electrowetting cylindrical lens, as introduced in Ref. 19. In this design, the two short sidewalls and roof are made of quartz glass, and the two long sidewalls and bottom are made of ITO glass. For an electrowetting cylindrical lens, the wetting angle between the two liquids and the long sidewall varies with the

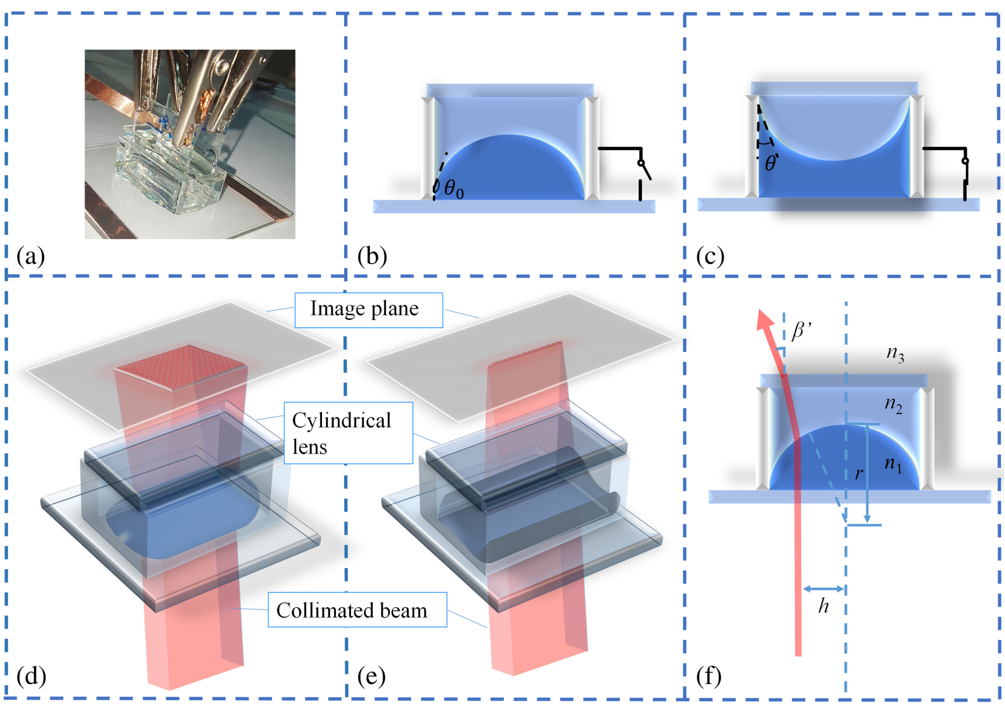

Fig. 1 Schematics of an electrowetting cylindrical lens: (a) photograph of the electrowetting cylindrical lens and method of voltage application; (b) initial liquid interface shape of the electrowetting cylindrical lens without voltage application; (c) liquid interface shape of the lens under voltage application; (d) diverging beam path diagram of the lens; (e) convergent beam path diagram of the lens; and (f) diagram for focal length calculation of the electrowetting cylindrical lens.

applied voltage, as shown in Figs. 1(b) and 1(c). The initial wetting angle, shown in Fig. 1(b), can be described using Young's equation:[20]

$$\cos\,\theta_0 = \frac{\gamma_{w1} - \gamma_{w2}}{\gamma_{12}}. \tag{1}$$

Here θ_0 is the initial wetting angle. γ_{w1}, γ_{w2}, and γ_{12} are the interfacial tensions between the wall and the nonconductive liquid, the wall and the conductive liquid, and the conductive liquid and the nonconductive liquid, respectively. The wetting angle θ, shown in Fig. 1(c), which varies with the applied voltage during the electrowetting phenomenon, can be determined using the Young–Lippmann equation:

$$\cos\,\theta = \cos\,\theta_0 + \frac{\varepsilon_0 \varepsilon_r}{2d\gamma_{12}} U^2. \tag{2}$$

Here d is the thickness of the dielectric layer coated on the electrode, U is the value of the externally applied voltage, ε_0 is the vacuum dielectric constant, and ε_r is the relative dielectric constant of the dielectric layer. The cylindrical lens gradually changes from a concave lens to a convex lens with increasing applied voltage, as shown in Figs. 1(d) and 1(e). From Figs. 1(d) and 1(e), we can clearly see the beam shaping process of the electrowetting cylindrical lens.

The cavity width of the cylindrical lens is recorded as D, and the curvature radius r of the double-liquid interface can be described as follows:

$$r = \frac{D}{2\cos\theta}. \tag{3}$$

Figure 1(f) shows the optical path of the paraxial light passing through the lens. The effective focal length f of the electrowetting cylindrical lens can be expressed as

$$f = \frac{r}{n_2 - n_1}. \tag{4}$$

Here n_1 and n_2 are the refractive indices of the two liquids, respectively. The optical power of the cylindrical lens can be expressed as follows:

$$\phi = \frac{1}{f} = \frac{n_2 - n_1}{r}. \tag{5}$$

Combining Eqs. (2), (3), and (5) yields

$$\phi = \frac{2(n_2 - n_1)\cos\theta}{D} = \frac{2(n_2 - n_1)}{D}\left(\cos\,\theta_0 + \frac{\varepsilon_0\varepsilon_r}{2d\gamma_{12}}U^2\right) = \phi_0 + \frac{(n_2 - n_1)\varepsilon_0\varepsilon_r U^2}{Dd\gamma_{12}}. \tag{6}$$

Then

$$\Delta\phi = \frac{(n_2 - n_1)\varepsilon_0\varepsilon_r U^2}{Dd\gamma_{12}}. \tag{7}$$

From Eq. (7), we find that to obtain a wider focal length range at lower applied voltages, the parameters of the liquids (including the refractive index difference $n_2 - n_1$ and the interfacial tension γ_{12}), and the dielectric layer (including the relative dielectric constant ε_r and the thickness d) should be appropriately selected.

According to Antonoff's rule, the interfacial tension between the oil and water can be expressed as[21]

$$\gamma_{12} = |\gamma_1 - \gamma_2|. \tag{8}$$

For two immiscible liquids, γ_1 and γ_2 represent their surface tensions. This is why we selected lower-surface-tension-difference liquids in the experiment.

3 Experiment

According to the theoretical analysis in the second part, there are mainly two methods to reduce the applied voltage, one of which is modifying the properties of the dielectric layer or liquids. Increasing the dielectric constant or decreasing the thickness of the insulating film requires a higher processing technology, and the expected zoom effect cannot be achieved using this method due to electrolysis or breakdown as introduced in Sec. 1.

Therefore, we attempted to reduce the liquid/liquid interfacial tension to lower the applied voltage. To ensure a difference in the refractive indices between the two liquids, we did not select an ionic liquid whose refractive index is closer to that of the packaging solution but rather tried to reduce the surface tension of the salt solution. The interfacial tension between two immiscible liquids is always proportional to the difference between the surface tensions of these liquids based on the Antonoff's rule, which is applicable for most oil–water and oil–salt solution systems. Moreover, the surface tension of the salt solution is always higher than that of oil. Hence, if the type of nonconductive liquid (i.e., the oil) remains the same, the surface tension of the conductive liquid (i.e., the salt solution) should be reduced, which can be easily done by adding a small amount of water-soluble surfactant or lower-surface-tension liquid to the original salt solution. Ethanol was chosen as the lower-surface-tension liquid in the experiment, as it can dissolve with the salt solution, and its refractive index is close to that of water. The density, refractive index, transmissivity, and wettability of the liquids are typically considered in the selection of liquids in the electrowetting lens. Considering the above conditions, n-dodecane[16] and KCL solution[22] were selected as the initial two liquids based on the literature research. To verify the correctness and rationality of this idea, three types of solutions with a low-surface tension were obtained by mixing ethanol with the original conductive solution by mass, and the fourth type of conductive solution was obtained by adding drops of surfactants into the original salt solution. The surface tension of the oil and of the four types of salt solution, the wetting properties of different liquid pairs under different applied voltages, the focal length variation range of the electrowetting cylindrical lens filled with different salt solutions, and the actual imaging of the different cylindrical lenses were observed and measured sequentially in this study. Thus the effectiveness of the method in reducing the applied voltage was demonstrated.

3.1 Surface Tension Measurement

n-Dodecane and 5% KCL solutions served as the nonconductive and original conductive solutions in the electrowetting cylindrical lens, respectively. A 5% KCL solution was recorded as conductive solution 1. Mixtures of 5% KCL solution and ethanol at mass proportions of 19:1, 7:3, and 2500:1 served as conductive solutions 2, 3, and 4, respectively. It must be noted that we chose the first three solutions simply because of the ease in which solutions with different surface tensions can be prepared and did not select them as the final lens material.

The surface tensions of all the five liquids were measured using the hanging drop method. A certain amount of liquid was suspended at the end of the capillary, as shown in Fig. 2(a).

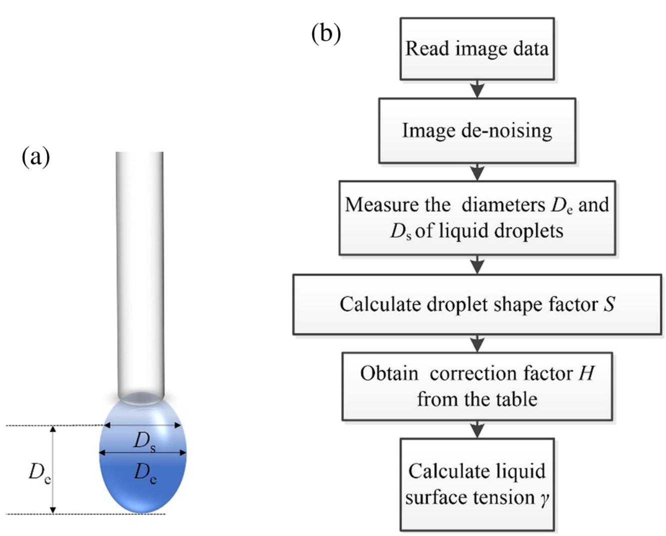

Fig. 2 (a) Schematic of measuring the surface tension using the hanging drop method. (b) Flowchart of the surface tension calculation by software.

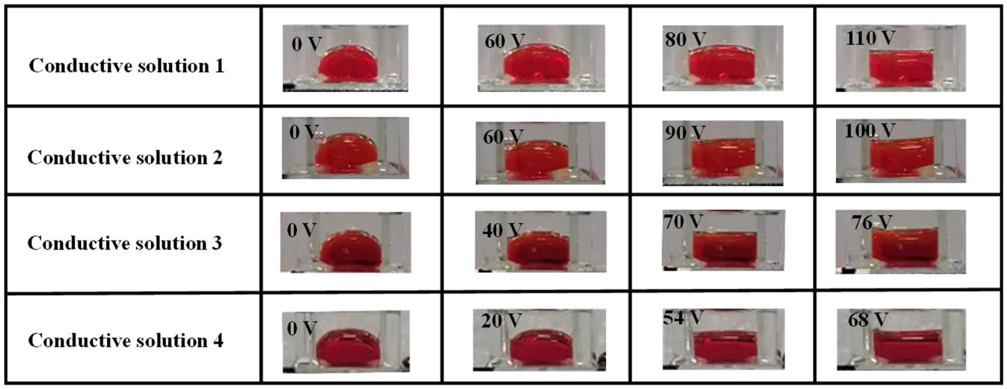

Fig. 3 Front views of electrowetting lenses containing conductive solutions 1 to 4 under different voltages.

The surface tension of the liquid is determined using the following equation:

$$\gamma = \frac{g(\rho_1 - \rho_0)D_e^2}{H}, \qquad S = \frac{D_s}{D_e}. \tag{9}$$

In Eq. (9), γ is the surface tension of the liquid to be measured, g is the gravity constant, ρ_1 is the density of the liquid to be measured, ρ_0 is the density of air, D_e is the maximum diameter of the droplet in the horizon, D_s is the horizontal diameter of the droplet at a distance of D_e from the bottom of the liquid, S is the calculated shape factor, and H is the modified shape factor related to S, which can be obtained from the table provided in Ref. 23. The surface tension can be obtained using MATLAB based on Eq. (9), as shown in Fig. 3(b). The front view of the liquid drop was imaged, then imported into MATLAB, and finally denoised. The D_s and D_e values of the droplet were measured, and S was calculated. The modified shape factor H was determined utilizing the data table. The density of the liquid was measured using the pycnometer method ($\rho = \frac{m}{v}$, where ρ is the density of the liquid to be measured, m is the mass, and v is the volume). Finally, the surface tension could be determined.

Antonoff's rule is the theoretical basis for the selection of the liquids in this study. However, it does not hold for every liquid–liquid interface. Therefore, we additionally measured the interfacial tension directly. Although we used the same hanging drop method to measure the interfacial tension, the droplet to be measured was not hung in air but in n-dodecane. Moreover, ρ_0 in Eq. (9) is the density of n-dodecane. Table 1 presents the measured values of the density, surface tension, refractive index, and interfacial tension with n-dodecane, which is the experimental solution. Clearly, the interfacial tension between the two liquids is largely consistent with the difference between the surface tensions of the two liquids. In other words, the Antonoff's rule is applicable for the liquids selected used in our electrowetting lens. We prefer measuring the surface tensions of the two liquids to evaluate the interfacial tension preliminarily in future liquid estimate experiments. This is because the surface tension is easier to measure than the interfacial

Table 1 Physical properties of the solutions selected.

	Density (g/ml)	Surface tension (N/m)	Refractive index	Interfacial tension in n-dodecane solution (N/m)
n-Dodecane	0.7658	0.026	1.4185	—
Conductive solution 1	1.0268	0.076	1.3365	0.050
Conductive solution 2	1.0145	0.056	1.3440	0.031
Conductive solution 3	0.9712	0.039	1.3515	0.013
Conductive solution 4	1.0268	0.035	1.3365	0.009

tension given the ease of droplet formation in air and the lower amount of data that need to be measured if several conductive and nonconductive liquids are paired for testing.

Table 1 shows that an increase in the proportion of alcohol solution reduces the surface tension of the prepared conductive solution, and the surfactant has a remarkable influence on the surface tension. The surface tension of n-dodecane remains unchanged. Therefore, the interfacial tension between the two liquids decreases when the conductive solution changed from 1 to 4 based on Eq. (8).

3.2 Wetting Properties

The process of manufacturing the cuboid cavity with an internal size of 20 mm × 10 mm × 8 mm to contain the two liquids has been introduced in detail in Ref. 17. The electrode on the sidewall was plated with 10 μm parylene N and a transparent single-component low-viscosity fluoropolymer protective coating. The four types of conductive solutions, listed in Table 1, were differently combined with n-dodecane, forming four pairs of liquids to fill the cavity and thus produce four different electrowetting cylindrical lenses. n-dodecane always occupied the upper part of the cuboid cavity. A camera was used to capture the changes at the liquid interfaces in the different cylindrical lenses under different applied voltages to study the influence of the oil/conductive solution interfacial tension on the wetting properties. A small amount of red pigment was added to the conductive solutions to obtain a clear interface of the two liquids. As shown in Fig. 3, the initial wetting angles without voltage application are largely the same under the four combined conditions. That is because when the oil/conductive solution interfacial tension changes, the difference between the oil/wall interfacial tension and conductive solution/wall interfacial tension varies synchronously. Therefore, the required applied voltage to obtain similar liquid interface shapes can reflect the control voltage, which decreased with the decrease in the oil/conductive solution interfacial tension, as shown in Fig. 3.

3.3 Zoom Range Calculation

MATLAB was used for gray processing, binarization, edge detection, and other operations on the liquid interface images under different voltages; extract the shape data of the liquid interface; and obtain the curvature value of the surface and thickness of the two liquids. Fig. 4 shows four images corresponding to the liquid interface shapes of different groups of solutions varying with the voltage. The curvature radii of all the curves were noted. Figure 4 shows that the initial liquid

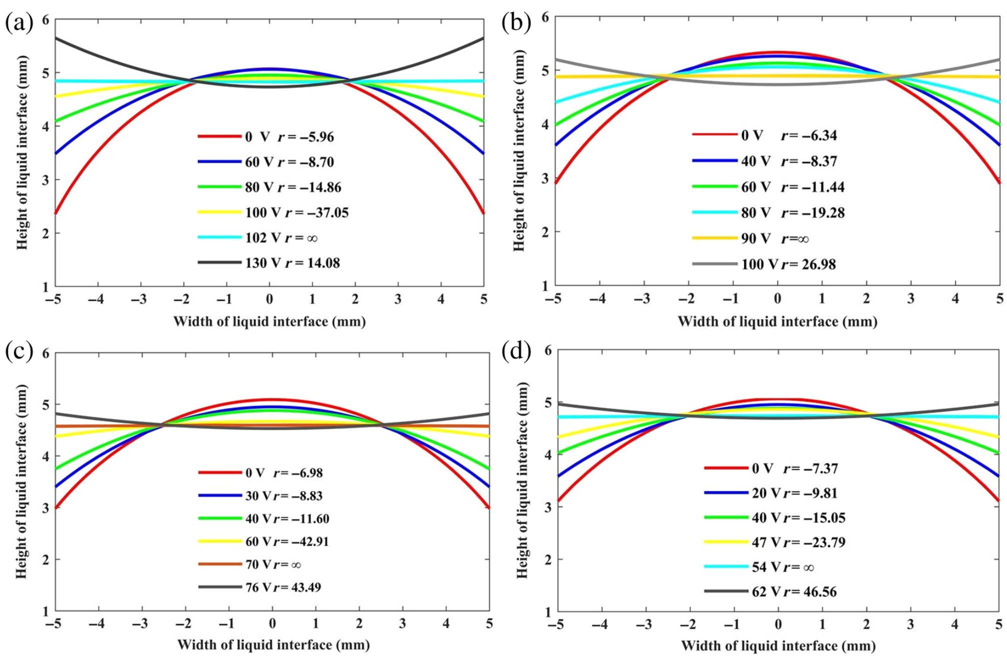

Fig. 4 Fitting curves of the liquid interfaces of the electrowetting cylindrical lenses filled with n-dodecane and conductive (a) solution 1, (b) solution 2, (c) solution 3, and (d) solution 4.

interface shapes and central curvature radii change a little without voltage application. The control voltages of the four different lenses with zero optical power were 102, 90, 70, and 54 V, indicating a significant voltage reduction effect.

To intuitively explore the change in the focal length of the lens with the voltage, Fig. 5 shows the curves of the focal length of different electrowetting cylindrical lenses calculated based on Eq. (4).

Figure 5 clearly shows that the lens filled with a lower-surface-tension conductive solution required a lower control voltage at the same focal length. This implies that the lower the surface tension difference between the two liquids is, the lower the control voltage required by the

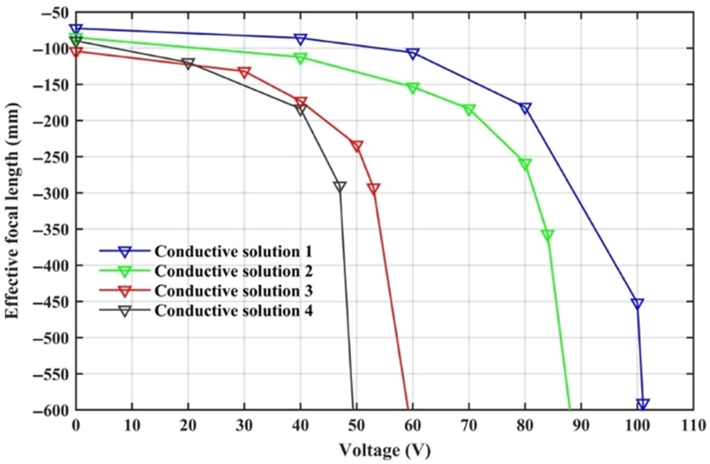

Fig. 5 Variation in the effective focal length of four electrowetting cylindrical lenses under different voltages.

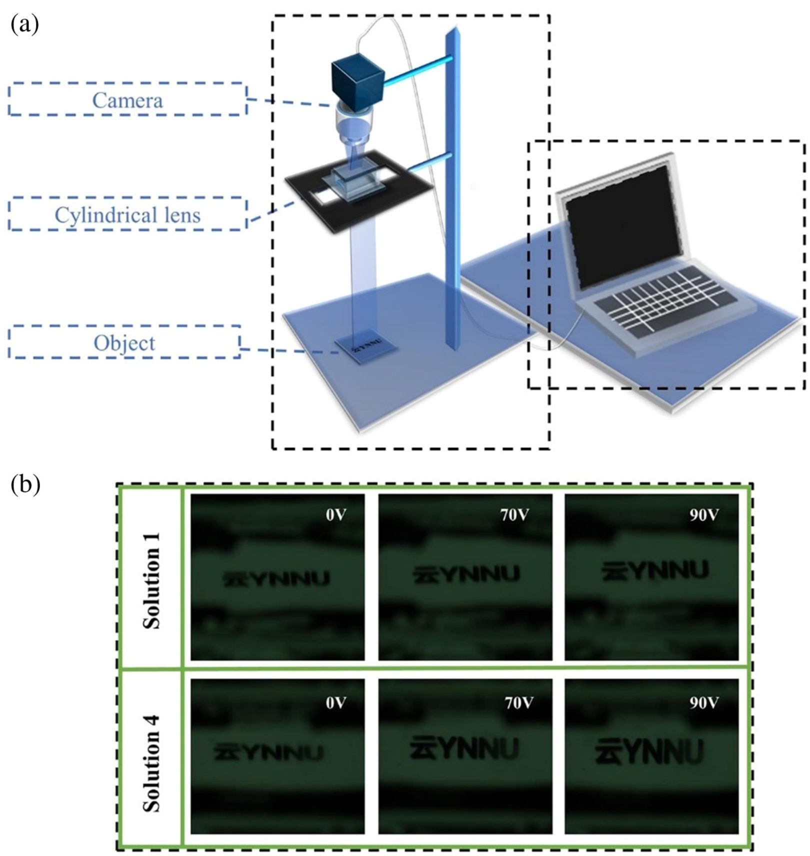

Fig. 6 (a) Experimental setup diagram and (b) experimental images captured by a camera.

electrowetting cylindrical lens, and this method can ensure approximately equal zoom range. The control voltage to obtain the infinite focal length decreased from 102 to 54 V, a reduction of 47%. Table 1 and Figs. 3–5 show that the method of reducing the control voltage by decreasing the surface tension of the salt solution is practically feasible, and adding surfactants to the salt solution provides the best effect.

3.4 Imaging Effect

A picture printed with "云YNNU" was selected as the object to observe the zoom effect of the lens, as shown in Fig. 6(a). The initial electrowetting cylindrical lens and the lens filled with conductive solution 4 showed the most evident voltage reduction effect. Figure 6(b) shows the images captured by the camera. Clearly, the imaging effect of the cylindrical lens under an applied voltage of 0 V changed little; however, under the same voltage, the zoom effect of the cylindrical lens filled with conductive solution 4 was more evident. When the applied voltages were 70 and 90 V, the control effect of the latter on the electrowetting cylindrical lens was evidently stronger than that of the former. For solution 4, the zoom effect under a voltage of 70 V was even more evident than that realized using solution 1 at 90 V, thus further proving the effectiveness of reducing the control voltage.

4 Conclusions

In this study, a method to reduce the control voltage of electrowetting cylindrical lenses was developed. The core of this method was to lower the interfacial tension between the two liquids. With the nonconductive liquid remaining unchanged, the addition of a low-surface-tension liquid into the original salt solution can help achieve this goal. In particular, a surfactant was found to be the optimal choice, as it can reduce the control voltage by 47% when the optical power of the lens is zero. This method can reduce the applied voltage while ensuring the zoom range, and it can be characterized by ease of application, low cost, and practicality. In the future, we will further reduce the control voltage of the electrowetting cylindrical lens by reducing the thickness of the dielectric film and the interfacial tension between the two liquids.

Disclosures

The authors have no conflicts of interest to declare regarding the publication of this article.

Code and Data Availability

All the data in support of the findings of this paper are available within the article or as supplementary material.

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