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Fabrication on low voltage driven electrowetting liquid lens by dip coating processes

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ABSTRACT

A low voltage driven electrowetting on dielectric liquid focus lens was fabricated based on a tiny glass tube which had been coated with ITO (indium tin oxide)–Al_2O_3–TiO_2–Teflon multilayered thin films on the inside. Method of sol–gel/chemical solution dip coating was used for the film preparation. A cambered interface between silicon oil and aqueous solution containing NaCl and sodium dodecyl sulfate (SDS) was used for the lens refraction. The curvature of the interface was adjusted by changing the applied voltage. The contact angle of aqueous solution in oil atmosphere was reduced from 155° to 67° when −10 V DC was applied. The leakage current was only 28 nA at that applied voltage and its focal length changed from −2 mm to infinity then to 10 mm.

1. Introduction

As new technology has greatly improved since the 21st century began, electrowetting on dielectric (EWOD) has been utilized in several optical applications such as reflection-type display [1,2], smart window [3] and liquid lens [4–8]. A tunable focus lens driven by EWOD has a significant potential to serve in micro-cameras instead of the traditional solid lens, due to its quick response time and simple fabrication methods. In 2000 Berge firstly reported their work on EWOD lens [4]. Afterwards, by controlling the curvature of the water–oil interface between two transparent thin plates, Atsushi Takei created a micro-focusing system which had a function on slanting view [6]. EWOD liquid lens can be also achieved on flexible polymer substrate such as polydimethylsiloxane (PDMS), as being reported in a paper by Chenhui Li [7].

The primary challenge for the EWOD liquid lens is how to reduce the applied required voltage. Among these mentioned focusing devices, all of them require to be loaded with around 70 V to 120 V to drive, which is difficult to achieve without the aid of an external power source for mobile devices. However, researchers on low voltage EWOD have proved that, in comparison to a single dielectric layer, multilayered dielectric films lead to a lower required level of applied voltage to make the contact angle have the same decrease [9,10]. In the following study, a double-layered insulating film was introduced, with one layer of high dielectric strength (Si_3N_4, SiO_2, Al_2O_3, etc.) and another with a high dielectric constant (TiO_2, BST) [11–13]. Understandably, it is complicated to coat patterned multilayers on the inner wall of a tube/cell by using vapor deposition and applying masking for the lens fabrication.

In this study, to make a simple and convenient process, a sol–gel dip coating procedure has been applied to fabricate a low-voltage driven EWOD liquid lens. Al_2O_3 was used to be the high dielectric strength layer while TiO_2 was the high dielectric constant layer in accordance with their individual dielectric properties [13,14]. Both were prepared by common sol–gel methods [15–17]. By jointly using chemical solution deposition (CSD) to coat the base layer of indium tin oxide (ITO) and the top hydrophobic layer with Teflon AF® 1600 inside a glass tube and then filling with a conductive aqueous solution and silicon oil, the EWOD liquid lens was obtained. By using an applied voltage of negative DC 10 V, with an imperceptible leakage current, the contact angle can be reduced from 155°to 67°and the focal length can be adjusted from −2 mm to infinity then to +10 mm.

2. Principle

In optical photography, to shoot a clear image, the object distance (S_o), image distance (S_i) and focal length (f) must obey the Gaussian lens formula [Eq. (1)].

$$\frac{1}{S_o}+\frac{1}{S_i}=\frac{1}{f} \tag{1}$$

In the case of a traditional solid lens, its focal length was determined when being manufactured. So it is necessary to adjust image distance inside the camera mechanism which requires sophisticated and complicated moving parts. That increases manufacturing costs, especially for a large number of micro-camera modules used in mobile devices.

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Whereas, due to the EWOD liquid lens ability to change its focal length with only the applied voltage, there would be no requirement to change the image distance anymore. As a result, it becomes possible to simplify the manufacturing process.

Fig. 1 gives the working principle of the EWOD liquid lens. When two immiscible liquids (aqueous solution and oil) are injected into a small tube, owing to the different interfacial tensions of these liquids, a curved interface is present between the two phases. Ordinarily, oil has a higher refractive index than water, so the type of lens (convex or concave) would be the same as the shape of the oil phase. In [Fig. 1(a)], in oil atmosphere, at the triple point and without applied voltage, water has an original contact angle (θ_0) higher than 90 °. As the interface is presenting a plano-concave lens, light passing through it would be spread and it produces a negative focal length. Furthermore, using EWOD technique, the contact angle can be reduced by an applied voltage. Exhibiting in [Fig. 1(b)], at a particular voltage, the contact angle can be reduced to 90 ° with a specific applied voltage (θ_v), so the interface appears to be flat. At this voltage, the passing light is not being refracted, hence the lens produces a focal length to infinity. Moreover, if the voltage increases, as shown in [Fig. 1(c)], the contact angle becomes lower than 90 ° and the interface converges the passing light, similar as what a plano-convex lens does.

In order to get the relationship between the applied voltage and focal length, a theoretical calculation is given as follows:

For a plano-convex/concave lens, the focal length satisfies Lensmaker's Formula [Eq. (2)], where f is the focal length of the lens; R is the radius of curvature; N is the relative refractive index which is a ratio of the absolute refractive index for oil (N_{oil}) and water (N_{H_2O}).

$$\frac{1}{f}=\frac{N-1}{R} \quad \left(N=\frac{N_{\mathrm{oil}}}{N_{\mathrm{H_2O}}}\right) \tag{2}$$

R can be obtained by a simple geometric calculation in Fig. 1(c), where D is the inner diameter of the tube [Eq. (3)].

$$\cos\theta_v=\frac{D}{2R} \tag{3}$$

The relation between applied voltage (V) and instant contact angle (θ_v) is shown in the Lippmann–Young's equation [Eq. (4)] [18], where θ_0 is the original contact angle and γ_{WO} is the original interfacial tension between aqueous phase and oil phase. At the same time, ε and d are the total dielectric constant and thickness of the dielectric multilayers (including all of the thin films except the conductive base layer), respectively. From the equation, for certain interfaces, increasing the applied voltage and decreasing the thickness d are two feasible ways to achieve a higher contact angle change.

$$\cos\theta_v = \cos\theta_0-\frac{V^2\varepsilon}{2d\gamma_{WO}} \tag{4}$$

By combing the formulas of Eqs. (2)–(4) together, an integrated theoretical equation of EWOD liquid lens can be established in [Eq. (5)]. Thus, it is obvious that after being fabricated, the applied voltage is the

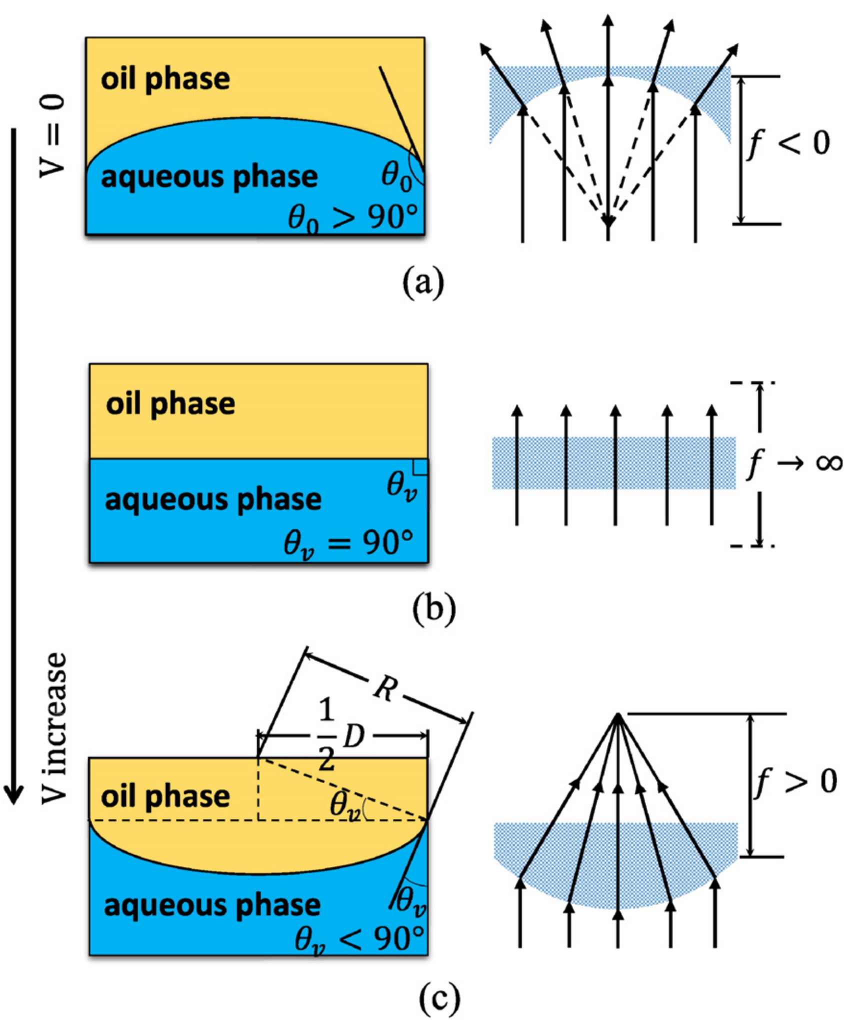

Fig. 1. Principle of the EWOD water–oil liquid lens.