第17卷　第6期
2009年6月

光学 精密工程
Optics and Precision Engineering

Vol.17　No.6
Jun. 2009

文章编号　1004-924X(2009)06-1397-06

带有悬浮锥形圆环的液体变焦透镜

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摘要：基于介质上电润湿效应提出了一种由覆盖有导电氧化铟锡(ITO)薄膜和疏水介质薄膜的玻璃片，悬浮在玻璃片上方的锥形金属圆环以及透镜中的液体组成的液体变焦透镜结构。通过改变施加在接地金属圆环和ITO控制电极之间的电压，实现了透镜液体的弯月面位置和曲率的可逆调整，从而改变透镜焦距。悬浮的金属圆环同时被用来使透镜中的水滴自居中，讨论了具有自居中效应的不同悬浮圆环形状对弯月面光学功率变化范围的影响。实验结果表明，施加40 V电压可以使透镜样品在2.5 cm和无限远之间聚焦，同时拥有高成像质量，光学功率变化范围达40 m^{-1}。本文设计的液体变焦透镜兼具低功耗、小尺寸和高度可逆等特性，在微透镜应用领域具有很大优势。

关　键　词：介质上电润湿；变焦透镜；液体透镜；表面张力
中图分类号：TH703　　**文献标识码**：A

Variable-focus liquid lens with suspended conical ring

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Abstract: A novel configuration of variable-focus liquid lens based on an electrowetting-on-dielectric technique is presented, which consists of a glass slide coated with a conductive Indium Tin Oxide (ITO) film, a hydrophobic dielectric film, a hollow conical metal ring suspended right above a gap between the slide and the ring, and the lens liquid (water). By changing the voltage applied to a grounded metal ring and a ITO control electrode, both the position and curvature of the liquid meniscus can be reversibly adjusted, and the focal length of the lens can be tuned. The shapes of the suspended ring in the present work are also designed to self-center the lens liquid, then influences of different shapes of the suspended rings on the variation of optical power of the meniscus are discussed. Experimental results show that the liquid lens at a good imaging quality is able to focus on objects away from 2.5 cm up to infinity at a 40 V power supply and also able to offer the variation range of the optical power up to 40 m^{-1}. Because of the properties such as low consumption, small sizes and high reversibility and so on, the demonstrated configuration provides great advantages in the field of microlens.

Key words: electrowetting on dielectric; variable-focus lens; liquid lens; surface tension

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Received date: 2009-01-20; **Revised date**: 2009-04-30.

Foundation item: Supported by the National Natural Science Foundation of China (Grant No. 10472055)

1 Introduction

Variable-focus lenses play an important role in many optical systems, such as cameras, telescopes, medical instruments and optical commutations. In these systems, focusing is usually achieved by lens displacement. However, miniaturization of such systems is complicated concerning the fabrication and assembly of tiny components. With continuing miniaturization trends in various fields, small variable-focus lenses for applications such as camera phones, hidden security cameras and endoscopes have been in great demand. It is desirable to implement systems without mechanical moving parts for reducing size and cost, or improving robustness and reliability.

2 Background

In recent years, researches of variable-focus liquid lens based on electrowetting-on-dielectric (EWOD) technique have attracted significant interests[1-6]. In contrast to those lens-displacement systems, liquid lenses based on EWOD technique change the shape of droplets to tune their focal length. EWOD is taken to directly change the surface tension and wettability of liquid droplets on the solid dielectric layer by varying electric potential applied to the electrodes, which are under the dielectric layer. The relation between the contact angle of droplets on the solid surface θ and the potential V is given by Lippmann-Young equation,

$$\cos\theta(V)=\cos\theta(0)+\frac{\varepsilon\varepsilon_0 V^2}{2d\gamma_{\text{gas-liquid}}}\ , \qquad (1)$$

where ε and d are the dielectric constant and the thickness of the dielectric layer respectively, ε_0 is the dielectric constant of free space, $\gamma_{\text{gas-liquid}}$ is the surface tension of gas-liquid interface. The lenses by Varioptic are constructed out of two different drops of liquid[1]. One of these drops can conduct electricity while the other can not. One drop is nestled on top of another in a conic-shaped ring of metal, and above and below them are thin panes of a solid translucent material to keep the drops in place. When the electrical charge is applied to the metal in a minute, the conductive fluid reacts and changes its shape, and the light passing through the panes bends in accordance with the shape of the curve between the two liquids. Fluid-focus lens is nearly a prototype of identical liquid lens by Philips electronics[2]. Philips' version uses a straight cylindrical metal ring enclosing the droplets instead of a conic-shaped ring. Bell lab's version involved a drop of conductive liquid on a metal plate as well, but this plate contained many electrodes that could 'fine-tune' the movement of the drop with each electrode activated[3]. In this paper, we present a novel configuration of liquid lens with a hollow conical metal ring. In contrast to the conic-shaped ring contacting tightly with the bottom panes in Varioptic's version, the metal ring in our version suspends right above a gap between the bottom glass slide and the ring, both the position and curvature of the water-air interface within the aperture of the metal ring can be reversibly adjusted to tune the focal length of the lens.

3 Configuration and fabrication

Fig. 1 shows a schematic cross section of our variable-focus liquid lens. The control electrode is a thin glass slide coated with a conductive ITO film, a 2.0 μm-thick dielectric layer of polyimide (ZKPI-306, POME Sci-tech Co.) and a 20 nm-thick hydrophobic film of Teflon(r) AF1600. In this paper, two immiscible fluids with different refractive indices are used: one is conductive water and the other is insulating air. A hollow conical metal ring is suspended over the slide to center the water droplet and provide a ground electrode. The ring is coated with a 20 nm-thick hydrophobic film (Teflon(r) AF1600), and then the hydrophobic film on the bottom surface of the ring is removed by mechanical polish to provide a hydrophilic surface. The liquid microlens is formed by the water-air interface within the aperture of the metal ring. During the focusing operation, the voltage between the metal ring and the ITO film could effectively low the interfacial tension and contact angle between the water and the dielectric film on the glass slide. A modification of the contact angle changes the volume of the water droplet located under the metal ring, and then causes a variation accordingly in both the curvature and position of the liquid meniscus inside the metal ring from *A* to *B*, as shown in Fig. 1, so the focal length of the microlens can be controlled.

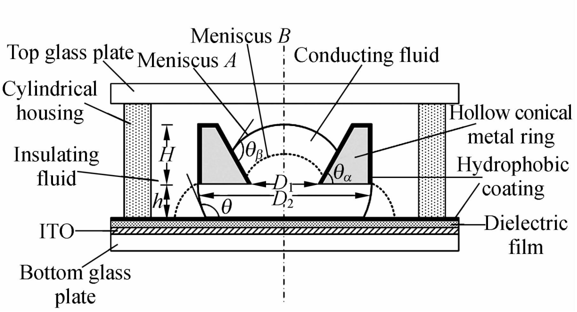

Fig. 1 Schematic cross section of variable-focus liquid lens based on EWOD with a suspended conical metal ring

Fig. 2 shows some typical metal ring shapes which could self-center the water droplet when the angle θ_β (in Fig. 1) is fixed. In the case of shape *A* and shape *C* (in Fig. 2), the meniscus is always convex. Shape *B* can easily realize a highly tunable liquid lens by moving the meniscus from a convex to a concave position, but it is difficult to be fabricated. We built a prototype of shape *A* with the following characteristic parameters: $D_1 = 3.0$ mm, $D_2 = 7.0$ mm, $\theta_\alpha = 60°$, $\theta_\beta = 110°$, $H = 3$ mm, $h = 1$ mm (in Fig. 1). De-ionized water is used as lens liquid. As we know, the variation of the optical power of the meniscus strongly depends on the shape of the conical ring and the charging volume ΔV of the water droplet located under the metal ring. One can obtain a higher sensibility of the microlens when h and D_2 become larger or D_1 becomes smaller. When the contact angle θ changes from 110° to 80° at a typical voltage of 40 V, ΔV is approximately 8 μL; ΔV is 32 μL by only changing the h from 1 mm to 2 mm, or 16 μL by only changing the D_2 from 7 mm to 14 mm.

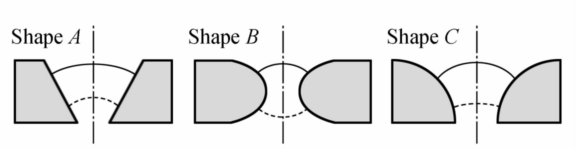

Fig. 2 Typical structures of metal ring for self-centering the droplet

4 Results and discussions

The gap between the ring and bottom slide, and the topography of the metal ring and the water volume has joint impacts on the focal length. A typical curve of the relation between the focal length and applied voltage obtained by injecting 50 μL de-ionized water is shown in Fig. 3. The experimental results show that the focal length saturates at a higher voltages (>40 V). It can be well explained by the saturation phenomenon of the contact angle[7-9]. In our case, Teflon(r) AF1600 is used as the hydrophobic film, so that the contact angle can only decrease from 110° to about 80° after the electrical potential is applied.

The lens can be driven by a d. c. voltage or an a. c. voltage. We could use a d. c. voltage up to 40 V to focus on objects away from 2.5 cm to infinity, and this only consumes energy of 0.2 μJ to charge the 300 pF capacitor formed by the

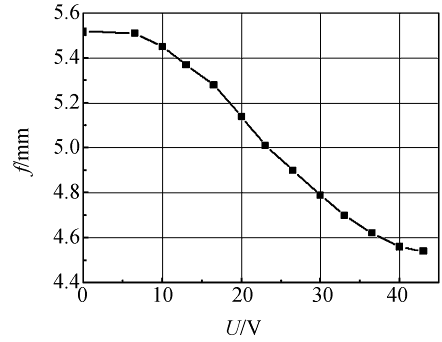

Fig. 3 Typical curve of focal length *vs* applied voltage

ITO electrode and the water droplet. When the object is away from 2. 5 cm to infinity the focal length can be adjusted from 4. 54 mm to 5. 52 mm correspondingly. The optical power (the reciprocal of the focal length measured in meters) of our lens, with its bottom diameter D_1 of 3 mm, could vary over a range of 40 diopters. This is accomplished by changing the contact angle θ from 80° to 110° which is typical for the water droplet on the hydrophobic layer of Teflon. If it has the same size as the lens in a human eye, its optical power range would be about 12 diopters which is 3 times as large as the optical power of the human eye.

In principle, our lens can be operated under two stable modes by injecting appropriate volume of water. In the case of the prototype mentioned above, the threshold is about 41 μL: when the water volume is larger than 41 μL, the lens will work in the first stable mode. As shown in Fig. 1, the meniscus moves from high position A to low position B by increasing the voltage, and both its curvature and position change as expected; However, when the volume is 31—41 μL, the lens will work in the second stable mode. The meniscus will be pinned at the bottom mouth of the metal ring, and only its curvature changes with the voltage. A volume of water smaller than 31 μL will make the lens fall into an unstable state.

Moreover, the dependences of the focal length versus the applied voltage are quite different in the two stable modes. In the first stable mode, the change of the focal length can be divided into two parts: one is caused by the curvature of the meniscus, which is decreased with an increasing voltage; the other is caused by the position of the meniscus, which strongly depends on the position of the imaging sensor. If the imaging sensor is positioned above the metal ring, the contributions of the position and curvature will enhance each other, while the contribution of curvature cancel out the one of position when putting the imaging sensor is under the bottom slide. In order to obtain an effective variable-focus lens, we position the imaging sensor above the ring, and the lens focus on closer objects when higher voltage is applied. In the second stable mode, the dependence of the focal length and applied voltages becomes simpler: the focal length increases with the applied voltage increasing, and thus our lens focuses on further objects when higher voltage is applied.

Dynamical focusing of our microlens worked in the second stable mode is demonstrated. A plate with two 2 mm-high letters is placed 2. 5 cm away from the microlens, and a rubber girl is about 50 cm away. Fig. 4(a)—4(d) show four video frames taken at increasing voltages. The initial focus is adjusted on the plate, as shown in Fig. 4(a). When the applied voltage increases to 22 V, the rubber girl comes into focus and becames clear (in Fig. 4(d)).

Generally, a blurred image occurs when light from the margin of a spherical lens comes to a shorter focus than light from the central portion. Furthermore, the lens refracts light of different wavelength and the dependence of the refractive index of the various materials (dispersion) forming the lens may result in chromatic aberration. The dispersion must be well corrected in order to obtain a high optical quality. Color correction can be done traditionally by adding some costly doublet components. However, liquid-based variable-focus lenses make achromatization straightforward: we can tune the optical properties of the fluids by mixing or dissolving well-chosen substances, and then make an achromatic liquid lens without using costly achromatization methods[4]. The images presented could be sharper when the optical aberrations are counteracted.

(a) 0 V (c) 15 V

(b) 10 V (d) 22 V

Fig. 4 Ability of focusing on objects at different distances

5 Conclusions

Using EWOD technique, we have developed a novel variable-focus liquid lens with a suspended metal ring. The prototype of the lens has shown some good qualities such as small size, low power consumption and no mechanically moving parts with a high variation range of optical power of 40 diopters. It has a promising prospect in many fields of optics where robustness, size, speed, power consumption and durability are critical[10].

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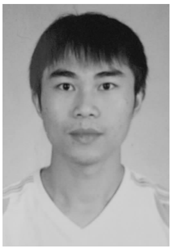

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●**下期预告**

时钟抖动下加速度测量值的数值双积分误差

谭晓昀,周贤中,许 娜,陈伟平,刘晓为
(哈尔滨工业大学 MEMS 中心,黑龙江 哈尔滨 150001)

采用蒙特卡洛分析法,对由于时钟抖动造成的加速度计定位误差进行了系统的分析。仿真结果表明,在存在时钟抖动的情况下,加速度测量值是渐进服从高斯分布的,这个仿真结果与理论分析结果相吻合。同时,对积分距离的方差与时钟抖动之间的关系进行了详细的分析。理论及仿真分析结果都表明了噪声的数值双积分的积分误差与时钟抖动的大小成正比。当输入是一个幅值为 1 *g*,周期为 1 s 的正弦波加速度信号时,1 s 后的数值双积分的积分误差与时钟抖动的比例系数为 0.261 1。