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Electrically-controlled and Liquid-based Optical Imaging Apparatus*

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Abstract: A kind of liquid-based and electrically-controlled optical imaging apparatus is provided, which is a cylindrical chamber holding three liquid layers. A kind of insulating liquid is sandwiched between two layers of conducting liquids. A layer of transparent electrode and a layer of insulating layer are coated inside the chamber in turn. Two different external voltages can be applied between the electrode and two layers of conducting liquids, which respectively control two liquid interfaces in the chamber. These two voltages can be matched appropriately to change the focal length and keep the image plane of the apparatus stable simultaneously. Taking the infinite object as an example and based on the Gauss Optics Theory, detailed calculations concerning the relationship between the voltages and the focal length of the apparatus are given. The relevant simulation result that the zoom ratio of the apparatus can be 1 : 1.5 shows that such an apparatus is a viable variable focal length optical imaging system.

Key words: Electrically-controlled; Variable focus; Liquid lens; Imaging apparatus

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0 Introduction

Optical lenses are optical devices that refract light to form an image of an object. They are fundamental components of many imaging systems, including viewing devices such as glasses, binoculars and telescopes, scientific instruments such as microscopes and spectroscopes, analog and digital cameras, video cameras, medical devices such as optical catheter and endoscopes, and the like. There are many types of optical lenses available today, manufactured from various materials with different characteristics.

Lenses having fixed focal lengths may typically require a mechanical or other optical compensation assembly to move the lenses so images are captured with the appropriate magnification. Both the mechanical and optical compensation techniques require precise control of the mechanical position of the lens. Additionally, precisely spaced cams or gears must be used to implement synchronized movements. Such conventional solutions have been considered to be complicated, fragile and thus expensive. The assembly together with the lens set may be heavy and slow to adjust. They are also not convenient to be implemented in small space, such as in miniature cameras used in mobile devices.

An alternative approach is to use lenses having variable focal lengths. Such lenses may have a variable surface or material. For example, a refraction-diffraction combined variable focal lens based on LCD Fresnel lenses has been previously proposed[1-2]. Electrically motivated, the LCD Fresnel lenses can adjust the focal length by changing the refractive index of the LCD material without involving any motorized movements. However, disadvantages such as large chromatic aberrations and difficulties in keeping the image plane fixed pose an obstacle to the practical use of these lenses.

Variable focal lenses based on the electrowetting[3-8] principle have also been proposed. In 2004, researchers at Philips reported a double-liquid variable-focus lens based on electrowetting. Unlike conventional solutions, a double-liquid lens changes its focal length electrically rather than mechanically. The disadvantages of other variable-focus lenses, such as the LCD Fresnel lenses described above, are also avoided. However, one double-liquid lens cannot keep the image plane stable while it changes the focal length. A fixed image plane ensures that

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the acquired image is properly focused and formed on the image acquisition surface, such as a film or image sensor. In order to meet the two requirements at the same time, two liquid lenses are required, as simply pointed out recently by Hentriks et al in 2006[6]. After that, a novel lens system mainly composed of two double-liquid variable-focus lenses was designed by our research group[9-10].

In this paper, an optical imaging apparatus with single, triple-layer, double-liquid variable focal lens is provided. Such a design arranges two electrically-controlled liquid interfaces in the same cylindrical chamber. Compared with our previous designs[9-10], it can achieve smaller size and there are two fewer parallel plat plates in structure. By applying appropriate voltages to control two liquid interfaces, the apparatus can realize zooming and focusing to observe a large area with small magnification or a small area with large magnification. The theory and design method for the apparatus are discussed.

1 Structure and principle of the optical imaging apparatus

An optical imaging apparatus with single, triple-layer, double-liquid variable focal lens is described in Fig. 1, which is formed of a cylindrical chamber enclosing three liquid layers , with one liquid layer (insulating liquid such as bromododecane with refractive index n_1) between two liquid layers holding the same liquid (conducting liquid such as NaCl aqueous solution with refractive index n_2, $n_2 < n_1$). These two kinds of liquids are immiscible and have the same density so that the liquid interfaces between the two liquids act as a spherical lens[4]. An electrode layer disconnected in the middle and a hydrophobic dielectric layer with thickness d and relative permittivity ε_r are coated inside the cylindrical chamber successively. Voltages U_1 and U_2 are applied between the conducting liquid and the electrode layer to control the contact angles θ_1 and θ_2, thus control the radii of interface curvatures R_1 and R_2 (R_2 is infinity in Fig. 1) due to the electrowetting effect. The relationship between the applied voltage U_1 or U_2 and the changeable radius R_1 or R_2 can be described as follows

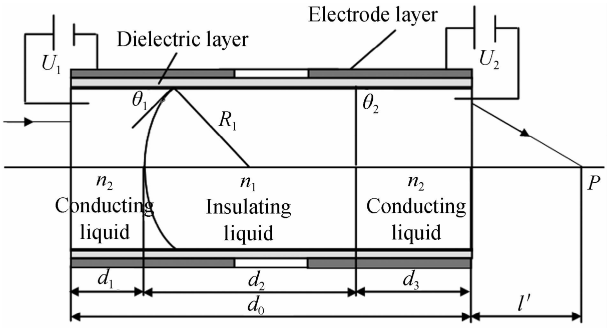

Fig. 1　Schematic of the optical imaging apparatus with a planar liquid interface

$$R_1 = -a/[\cos\theta_0 + \varepsilon_0\varepsilon_r U_1^2/(2\gamma_{12}d)] \tag{1}$$

$$R_2 = -a/[\cos\theta_0 + \varepsilon_0\varepsilon_r U_2^2/(2\gamma_{12}d)] \tag{2}$$

where a is the inner radius of the cylindrical chamber, θ_0 is the initial contact angle when there is no external voltage applied, ε_0 is the permittivity of free space and γ_{12} is the tension coefficient of liquid interface.

To enable the lens mentioned above to image, we assume the radius of the first liquid interface R_1 is always positive to make it convergent. When the applied voltage U_1 makes R_1 smaller (or larger), if the image plane remains fixed, the applied voltage U_2 must decrease (or increase) the convergence effect of the second liquid interface to make the convergence angle on the image plane decrease (or increase) and the combined focal length increase (or decrease). If the voltages are matched appropriately, the lens would be desirable to provide an optical imaging apparatus and method that are capable of achieving a variable focal length and an invariable image plane without any mechanical movements.

2 Analysis of the optical imaging apparatus

In this section, we take infinite object distances as example to explain how such an optical imaging apparatus can focus and zoom. Firstly, let us consider a special case when the first liquid interface is shown with a positive curvature while the second liquid interface is shown with a planar curvature, referred to Fig. 1.

When the second liquid interface becomes a plane under some external voltage, such an interface has no contribution to the total focal power, which only changes the focus position of the apparatus. With various optical distances as illustrated in the figure, the distance l' between the image point P and the triple-layer, double-liquid variable focal lens can be expressed as

$$l' = \frac{n_0}{n_2}\left(\frac{n_2}{n_1}\left(\frac{n_1 R_1}{n_1 - n_2} - d_2\right) - d_3\right) \tag{3}$$

When the voltage U_1 makes the radius of the first liquid interface larger, the voltage U_2 must make the radius of the second liquid interface negative to keep the image plane fixed. With various optical distances and other parameters as illustrated in Fig. 2, the distance l'' between the image point P' and triple-layer, double-liquid variable focal lens can be expressed as

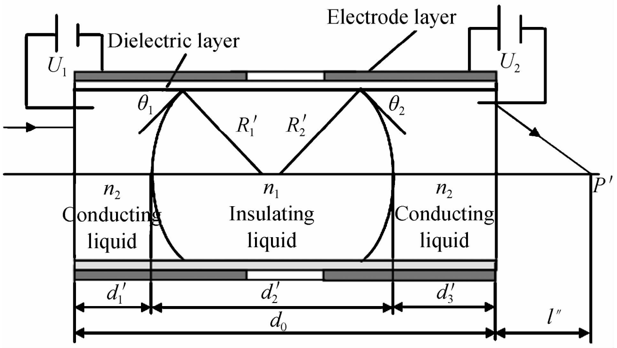

Fig. 2 Schematic diagram of the optical imaging apparatus with variable liquid interface radii

$$l''=\frac{n_0}{n_2}\left\{\left[n_2R_2'\left(\frac{n_1R_1'}{n_1-n_2}-(d_0-d_1'-d_3')\right)\right]\Big/\left[n_1R'_2+(n_2-n_1)\left(\frac{n_1R_1'}{n_1-n_2}-(d_0-d_1'-d_3')\right)\right]-d_3'\right\} \quad (4)$$

To make the image plane invariable, i. e. , to make the image point P' and the distance l'' fixed, let

$$l''=l' \quad (5)$$

which results in

$$R_2'=\left[\left(l'+\frac{n_0}{n_2}d_3'\right)\left(\frac{n_1R_1'}{n_1-n_2}-(d_0-d_1'-d_3')\right)\cdot(n_2-n_1)\right]\Big/\left[n_0\left(\frac{n_1R_1'}{n_1-n_2}-(d_0-d_1'-d_3')\right)-n_1\left(l'+\frac{n_0}{n_2}d_3'\right)\right] \quad (6)$$

Applying geometric relations between the various optical distances illustrated results in

$$d_1'=k_1d_0+(2R_1'^3+2R_1'^2(R_1'^2-a^2)^{1/2}-3a^2R_1'-2a^2(R_1'^2-a^2)^{1/2})/(3a^2) \quad (R_1'<0) \quad (7)$$

$$d_1'=k_1d_0+(2R_1'^3-2R_1'^2(R_1'^2-a^2)^{1/2}-3a^2R_1'+2a^2(R_1'^2-a^2)^{1/2})/(3a^2) \quad (R_1'>)0 \quad (8)$$

$$d_3'=k_2d_0+(-2R_2'^3-2R_2'^2(R_2'^2-a^2)^{1/2}+3a^2R_2'+2a^2(R'^2_2-a^2)^{1/2})/(3a^2) \quad (R_2'<0) \quad (9)$$

$$d_3'=k_2d_0+(-2R_2'^3+2R_2'^2(R_2'^2-a^2)^{1/2}+3a^2R_2'-2a^2(R'^2_2-a^2)^{1/2})/(3a^2) \quad (R'_2>0) \quad (10)$$

where k_1 and k_2 are the volume percentage of two conducting liquid layer over the total lens volume.

In Eq. (6), the relationship between R_1' and R_2' is given since d_1' is the function of R_1' and d_3' is the function of R_2'. When the applying voltage U_1, which determines R_1', is known, R_2' can be solved by a numerically iterative method based on Eq. (6). Since there exists one-to-one correspondence between the applied voltage and the interface radius, as shown in Eqs. (1) and (2), the relationship between R_1' and R_2' can be readily converted into that of U_1 and U_2. The simulation result for the relationship of U_1 and U_2 is shown in Fig. 3, with $\varepsilon_r=1.993$, $\gamma_{12}=38.1\times10^{-3}$ N/m, $n_1=1.55$, $n_2=1.38$, $d_0=6$ mm, $a=1$ mm, $k_1=k_2=1/3$ etc.

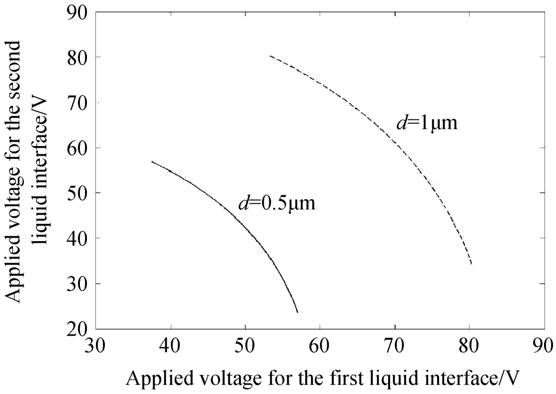

Fig. 3 Relationship curves for the applied voltages on the two liquid interfaces

On the basis of Gaussian optical theory, the focal length of optical imaging apparatus can, therefore, be expressed as

$$f=\frac{n_0n_1R_2'R_5'}{(n_1-n_2)\left(n_1R_5'+(n_2-n_1)\left(\frac{n_1R_2'}{n_1-n_2}-d_3'\right)\right)} \quad (11)$$

The relationship between the voltage and the focal length f of the lens is simulated in Fig. 4.

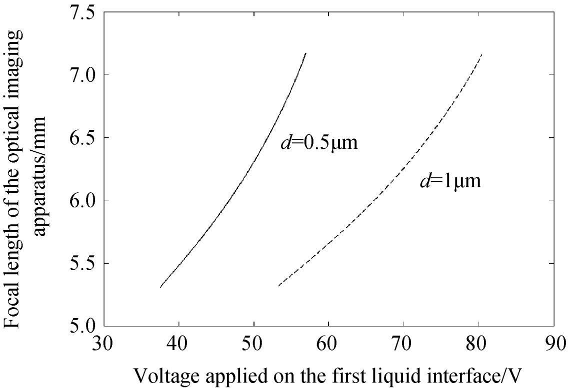

Fig. 4 Relationship curves for the applied voltage and focal length of optical imaging apparatus

3 Conclusions

The analysis and calculations above provide solid basis for the optical imaging apparatus to realize focusing and zooming simultaneously. In our example, the position of the image plane is settled when the first interface radius is about 1.2 mm and the second interface radius is infinity. In this case, the applied voltages over these two interfaces are correspondingly 54 V (or 76 V) and 33 V (or 44 V) with dielectric layer thickness 0.5 μm(or 1 μm), and the focal length of the optical imaging apparatus is about 6.7 mm.

When the applied voltage increases to make the first interface radius larger (or smaller), the second interface radius must be negative (or positive) under the external voltage to keep the image plane invariable. Now the focal length of the apparatus becomes larger (or smaller), which can range from about 5.2 mm to 7.2 mm under the action of two applied voltages. That is, the focal length of the apparatus can be varied by simply changing the applied voltages, while the image plane is kept invariable.

It is appreciated by one of ordinary skill in the art that the lens apparatus is shown with two conducting layers and one insulating layer for illustration purposes only. A lens having two insulating layers and one conducting layer may also be used to provide a variable focal length and an invariable image plane.

According to another embodiment of the design, as pointed out previously by our research group, an optional fixed lens may be combined with the apparatus described above. The fixed lens may be used to improve the optical properties of the optical imaging apparatus while keeping the image plane invariable for a variable focal length. Those optical properties may include, for example, dispersion, zoom capabilities, and chromatic aberration, among others.

For all results, the fringe fields around the contact line have not be taken into account. Their contribution to this system is still under investigation.

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基于液体的电控光学成像系统

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摘　要：提出一种基于液体的电控光学成像器件，其结构是一个容纳有三层液体的圆柱容器，上下两层是导电液体，中间一层是油性液体.圆柱容器的内壁依次涂覆了透明导电层和绝缘介质层.在透明导电层与上下导电液体间施加两个不同的外部电压，分别用来控制容器中两个液体界面的形状.两个外加电压的适当匹配使该光学成像器件在焦距变化的同时保证像面位置不动.文章以器件对无穷远处成像为例，基于高斯光学理论对器件做了详细的计算，给出了两个外加电压的匹配关系以及系统的焦距表达式，并对系统做了相关的模拟分析，分析的结果表明本文所设计的光学成像器件的变倍比可达 1∶1.5，体现该器件是一种可靠的变焦光学成像器件.

关键词：电控；变焦；液体透镜；成像器件

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