LC-lens array with light field algorithm for 3D bio-medical applications

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ABSTRACT

In this paper, liquid crystal lens (LC-lens) array was utilized in 3D bio-medical applications including 3D endoscope and light field microscope. Comparing with conventional plastic lens array, which was usually placed in 3D endoscope or light field microscope system to record image disparity, our LC-lens array has higher flexibility of electrically changing its focal length. By using LC-lens array, the working distance and image quality of 3D endoscope and microscope could be enhanced. Furthermore, the 2D/3D switching ability could be achieved if we turn off/on the electrical power on LC-lens array. In 3D endoscope case, a hexagonal micro LC-lens array with 350um diameter was placed at the front end of a 1mm diameter endoscope. With applying electric field on LC-lens array, the 3D specimen would be recorded as from seven micro-cameras with different disparity. We could calculate 3D construction of specimen with those micro images. In the other hand, if we turn off the electric field on LC-lens array, the conventional high resolution 2D endoscope image would be recorded. In light field microscope case, the LC-lens array was placed in front of the CMOS sensor. The main purpose of LC-lens array is to extend the refocusing distance of light field microscope, which is usually very narrow in focused light field microscope system, by montaging many light field images sequentially focusing on different depth. With adjusting focal length of LC-lens array from 2.4mm to 2.9mm, the refocusing distance was extended from 1mm to 11.3mm. Moreover, we could use a LC wedge to electrically shift the optics axis and increase the resolution of light field.

Keywords: Liquid crystal lens, Endoscope, Microscope, Light Field

1. INTRODUCTION

Liquid crystal (LC) lens is an active optical element with capacity of electrically tunable focal length. The main stream of LC lens structure is fringing field controlled type LC lens proposed by S. T. Wu [1-2]. By applying voltage on surrounding electrodes, the fringing field from electrodes will modulate the distribution of orientation of liquid crystal molecules and induce lens-like phase retardation in LC cell. When an incident plane wave passing through LC cell, the wave will converge or diverge depending on the type of applied voltage to the electrodes. According the applied voltage power, the focal length of LC lens will be changed continuously without any shape chaining or mechanical movement.

The advantages of LC lenses are slight weight and small volume credited to the omission of mechanical devices [3]. LC lens arrays can be easily fabricated by etching neighbor hole-patterns as lens apertures on the ITO or aluminum electrode substrate. As shown in Figure 1, the size of LC lens array would not be much larger than a single LC lens device. In this paper, the liquid crystal micro lens arrays (LC-MLA) were utilized in two kinds of 3D bio-medical application: 3D endoscope and light field microscope. The 3D endoscopy can improve the speed and accuracy of surgery. 3D imaging also helps surgeons learn to control the instrument more quickly [4]. But the diameter of 3D endoscope is limited less than 1 mm for minimally invasive surgery. The LC lens array, which needs no extra mechanical device, can provide more views within the small endoscope tube. On the other hand, the light field microscope can record 3D information of specimen in a snapshot, which is suitable for recording living cells [5]. The challenge of light field microscope is the low resolution issue and narrow depth of field. The LC lens array, as plastic micro lens arrays, can be installed in light field microscope to record angular information. And the focusing plane of microscope would be adjustable by electrically changing the focal length of LC lens array. Furthermore, if we turn off the electric field on LC-lens array, the conventional high resolution 2D image would be recorded.

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2. 3D ENDOSCOPE

Current research indicates that there are three reasons a 3D endoscope will improve the speed of surgery. A LC lens array with 7 micro lenses in hexagonal arrangement was placed in front of a conventional endoscope. By adjusting the focal length of each LC lens, we successfully captured 7 micro images with view disparity recorded on the photo sensor of endoscope, and reconstructed the 3D image using integral imaging.

2.1 Convex-ring electrode LC-MLA

The electrode of each LC lens was fabricated as convex shape, instead of flat electrode shape, to improve the LC lens quality. The convex electrode can indicate better performance comparing with the flat electrode [6, 7]. The convex-ring electrode avoids stack overflow of the electric field at the center of the lens and permit shorter focal lengths. Such electrodes make it possible to work on a wider range of applied voltages, which gives more precise control over focusing.

The electrode pattern design is shown in Figure 1. Each lens can be applied with different voltages. The photo of the fabricated LC lens is shown in Figure 1(a) and a microscopic image of the hexagonal convex curved electrodes is shown in Figure 1(b). There are three other ways to make a curved photoresist; soft reflow process with a solvent vaporing technique, HBr/O2 Plasma treatment, and Gray-scale optical mask. Schematic of the liquid crystal is shown in Figure 1. It consists of two layers of ITO as electrodes, one is the patterned electrode on the top and other one is as ground electrode, two glass substrates of thickness 550 μm, a 35 μm thick layer of NOA81 as an insulating layer, an LC layer with cell gap of 30 μm, and two alignment layers are coated with PVA (poly-vinyl alcohol) and mechanically rubbed for homogeneous LC alignment. The rubbing directions of the two alignment layers are antiparallel, and the lens diameter for each one is 350 μm.

To evaluate the optical properties of this hexagonal LC lens array, we recorded the interference fringes of LC lens applied with different voltage from 0 ~ 5 Vrms. Figure 2 shows the appearance of the interference fringes changes as the LC directors reorients themselves in the applied electric field. The retardation difference of two adjacent constructive or destructive interference rings indicates a phase change of 2π, and the variation in phase retardation induced by the applied voltage shows how the electrical field alters the lens properties.

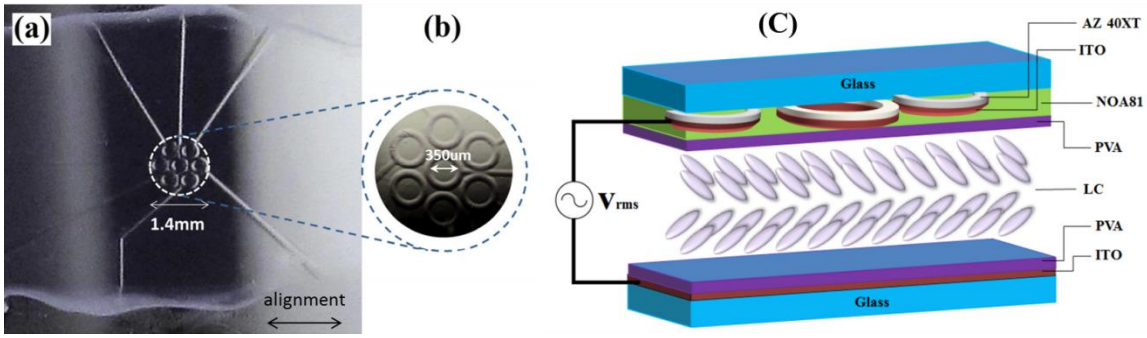

Figure 1. (a) Photo of the Hexagonal LC-MLA, (b) convex-ring electrodes pattern, and (c) Schematic of the LC-MLA structure.

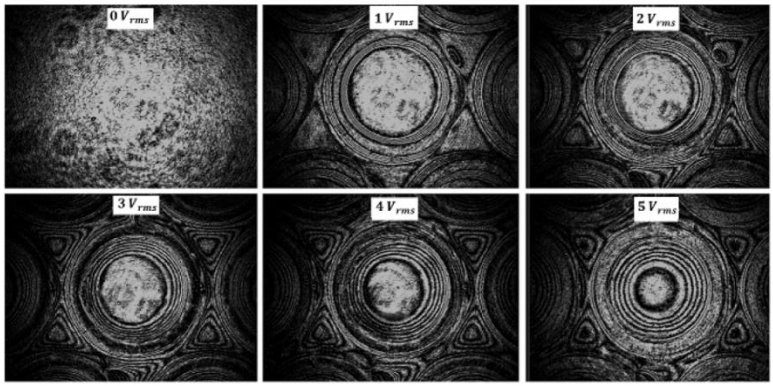

Figure 2. Interference fringes of convex-ring electrode LC lens driven with different voltages.

2.2 Experimental Results

The focal length of the convex-ring electrode LC lens array can be electrically varied by changing the effective refractive index of the LC region in each lens independently. Therefore we can implement 3-D imaging without moving the image sensor or the CCD sensor of endoscope. The LC lens can focus on the various depths or slices of the 3D object as the applied voltage varies. The sectional 2D images of under study can obtained at arbitrary depth positions by changing the focal length of the convex-ring electrode LC lens array for each lens. 3D image data may be constructed by capturing multiple 2D images of the 3D object and extracting the depth information according to various approaches [8, 9]. In our experiments, each lens can capture a 2D perspective image of the 3D scene from different viewing angles at tunable depths as shown in Figure 3. Thus, the system can record the depth-sampled image by properly synchronizing the 2D image to be captured by varying the focal length, as it shown in Figure 4(a). 3D image data is reconstructed using several 2D images captured by LC lens. We investigated the imaging properties of this LC lens when it was placed 2 mm from the objective lens of a side-view endoscope with a 20 × 25 mm^2 test object a sponge placed 73 mm from the LC lens. Figure 3(a) demonstrates a convex-ring electrode LC lens array that is mounted to a front view endoscope. We took images of the test object as shown in Figure 3(b). We captured images of an object from different viewing angles and processed them using integral imaging to reconstruct the 3D image of the object. Figure 4(b) is a reconstructed 3D image using the seven elemental images taken using the hexagonal convex-ring electrode LC lens array.

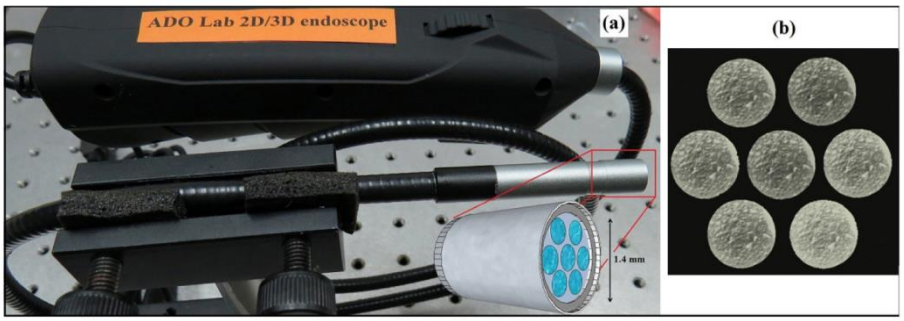

Figure 3. (a) The convex-ring electrode LC-MLA placed in front of the endoscope, (b) micro images in each LC lens.

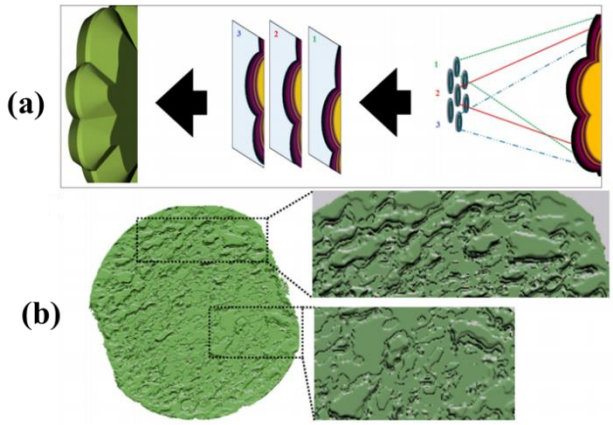

Figure 4. (a) Schematic of reconstructing a 3D image from 2D elemental images. (b) 3D image extracted from 2D elemental image array captured by the hexagonal LC-MLA.

3. LIGHT FIELD MICROSCOPE

The light field microscope is able to capture the light field information and reconstruct the 3D image in a snapshot [5,10-11]. However, the depth of field (DoF) of light field microscope is narrow, due to trade-off between focal length and effective resolution in the single aperture array light field system [12]. We proposed using the liquid crystal micro-lens array (LC-MLA) instead of fix lens array in light field microscope. By electrically changing the focal length of LC-MLA and montaging light field images at different focus plane, the DoF of light field microscope would be extended successfully.

3.1 High resistance layer of LC-MLA

The early reports on the LC lens controlled the ratio of lens diameter to LC cell thickness to optimize the LC lens quality. While the LC lens aperture becomes small (around few hundreds micrometers), it is difficult the fringing field propagates to the central region of lens aperture even we applied large voltage as 10 Vrms on electrodes of LC lens. The high resistance layer LC lens was proposed to generate smooth electric field in LC cell [13]. Figure 5(a) shows the fabrication process of high resistance layer LC-MLA. First, we etched the circular-hole on aluminum substrate as lens apertures. Then the material Nb_2O_x ($x = 4.7{\sim}4.9$) about 20 nm was sputtered on the electrode pattern as high resistance layer. The LC material was E7, LC cell gap was 60 um, and lens pitch was 350 um.

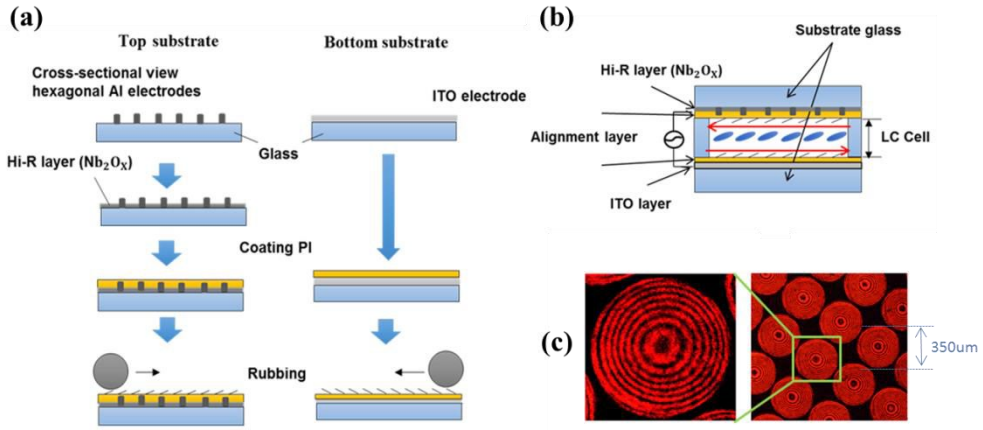

Figure 5. (a) Fabrication process of high resistance layer LC-MLA, (b) Schematic of LC-MLA structure, and (c) the interference fringes of LC-MLA driven at 2.7 Vrms, 200 kHz.

3.2 Extend depth of field

As Figure 6 shows, to obtain continuous and acceptable effective resolution ratio (ERR) [12], we should adjust the focal length of LC-MLA to make the ERR of boundary point a_1^- in the DoF_1 almost equal to the ERR of boundary point a_2^+ in the DoF_2. Therefore, we can combine these DoF ranges together and acquired longer range of DoF.

In our experiment, the object was placed at the focal length of objective lens. The focal length of LC-MLA was adjusted from 2.4 mm to 2.9 mm for different depth regions respectively. By using time sequential method we can combine these different depth regions together with ERR larger than 0.2. Finally, the total DoF of light field microscope with LC-MLA was extended to 11.3 mm, which is 11 times larger than with fix lens (focal length =2.43 mm) whose DoF is around 1 mm. Figure 7 shows the experiment result, a "paederus" as thick specimen of light field microscope. The refocusing plane of paederus's forefoot is at depth a= 17.25 mm, at where the light field image captured of focal length 2.9 mm LC-MLA (200 KHz, 2.7V) was more clear than of focal length 2.4 mm of LC-MLA (300 KHz, 2.7 V). On the other hand, when refocusing plane was at paederus's rearfoot, depth a= 7.2 mm, the light field image of focal length 2.4 mm of LC-MLA (300 KHz, 2.7 V) had more details than of focal length 2.9 mm of LC- MLA (200 KHz, 2.7V).

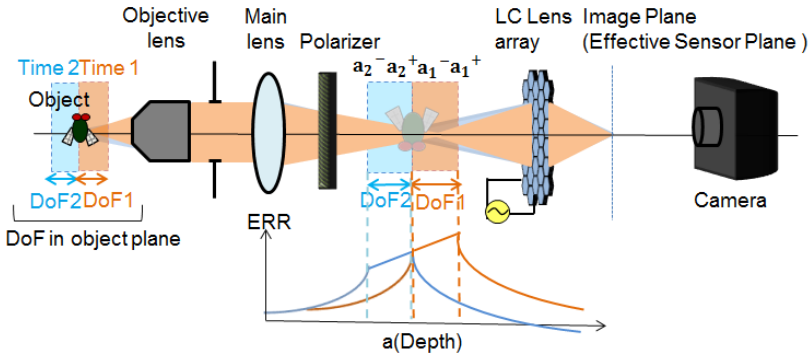

Figure 6. Extending DoF of light field microscope by montaging light field image with LC-MLA.

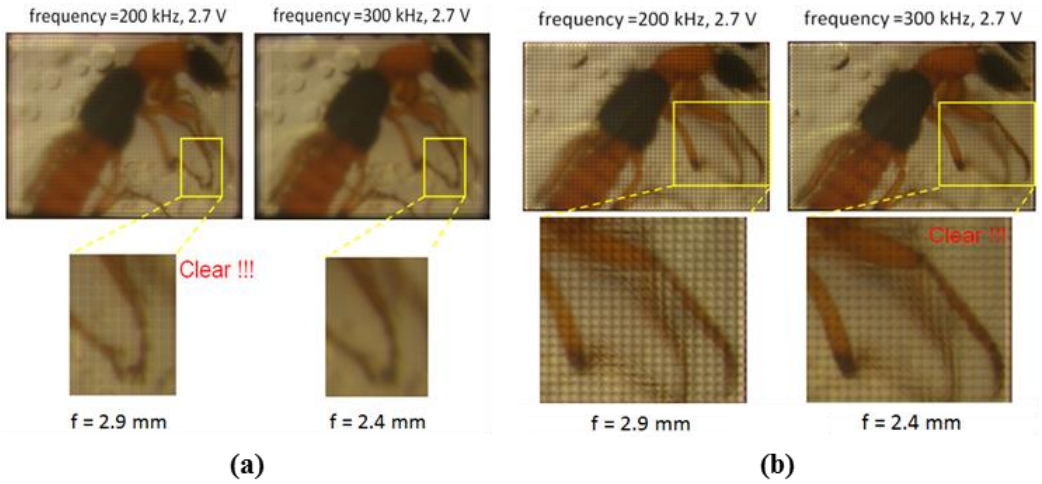

Figure 7. Refocusing images of paederus at different depth. (a) Refocusing plane at paederus forefoot a=17.25 mm, (b) Refocusing plane at paederus forefoot a=7.2 mm.

3.3 Enhancement of lateral resolution

Conventionally, the lateral resolution of light field microscope is much lower than of conventional microscopy, because the microscope sensor has to record both spatial and angular information simultaneously. Therefore, Lim et al. proposed to enhance the resolution of light field microscope by shifting the position of micro lens array in lateral direction [14]. In this paper, we utilized a liquid crystal wedge (LC wedge), instead of mechanically shifting micro lens array, to parallel shifting the optics axis by applying electrical voltage on the LC wedge or not. Then, we can obtain two light field images with displacement by optically shift the image plan instead of mechanically moving the micro lens array. By fusing these two light field images, we would obtain double sampling rate in lateral direction than conventional case. The refocused image combined from two light field images with displacement is shown in Figure 9.The image quality of combination image is high than of two original images, because the combination result was estimated with double information.

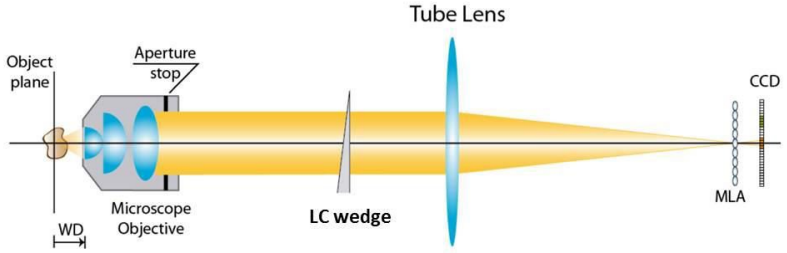

Figure 8. Enhance resolution of light field microscope with LC wedge.

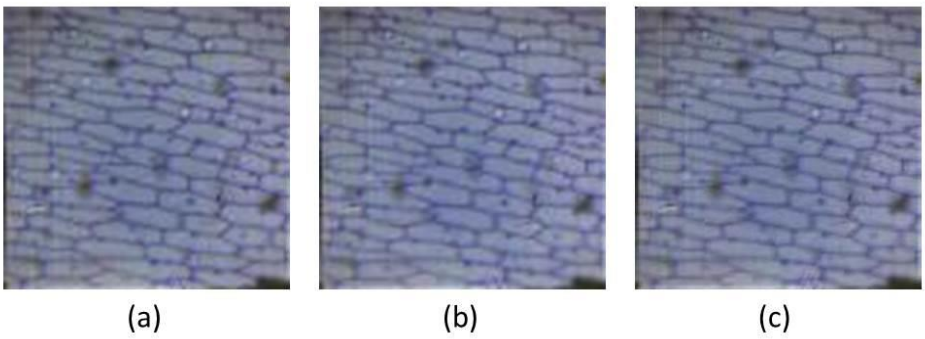

Figure 9. (a)(b) The refocused images of two light field images with displacement, and (c) the double resolution refocus image.

4. CONCLUSION

In this paper, liquid crystal lens (LC-lens) array was utilized in 3D bio-medical applications including 3D endoscope and light field microscope. In 3D endoscope case, we have successfully developed a convex-ring electrode LC-lens array for capturing 3D images by using a single sensor using integral imaging. The diameter of developed 3D endoscope is less than 1.4mm, which is close to conventional 2D endoscope. In the light field microscope case, we replaced the fixed micro lens array by a high resistance layer LC-MLA. By adjusting the focal length of LC-MLA from 2.4 mm to 2.9 mm, and fusing those light field images together, the total DoF of light field microscope was extended from 1 mm to 11.3 mm. Finally, we proposed a high resolution integral image microscope by using a LC wedge placed on the optics axis. By changing the refractive index of LC wedge, we could optically shift the image plan and gain a double lateral resolution image of light field microscope. It is worth to be mentioned that all the focal length tuning processing and optics axis shifting are electrically controlled, without any mechanical movement.

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