Optics Communications 412 (2018) 114–120

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dual-layer electrode-driven liquid crystal lens with electrically tunable focal length and focal plane

Y.A. Zhang, C.F. Lin, J.P. Lin, X.Y. Zeng, Q. Yan, X.T. Zhou *, T.L. Guo *

School of Physics and Information Engineering, Fuzhou University, Fuzhou 350002, China

ARTICLE INFO

Keywords:
Liquid crystal lens
Dual-layer electrode-driven
Focal length
Focal plane

ABSTRACT

Electric-field-driven liquid crystal (ELC) lens with tunable focal length and their depth of field has been extensively applied in 3D display and imaging systems. In this work, a dual-layer electrode-driven liquid crystal (DELC) lens with electrically tunable focal length and controllable focal plane is demonstrated. ITO–SiO_2-AZO electrodes with the dual-layer staggered structure on the top substrate are used as driven electrodes within a LC cell, which permits the establishment of an alternative controllability. The focal length of the DELC lens can be adjusted from 1.41 cm to 0.29 cm when the operating voltage changes from 15 V to 40 V. Furthermore, the focal plane of the DELC lens can selectively move by changing the driving method of the applied voltage to the next driven electrodes. This work demonstrates that the DELC lens has potential applications in imaging systems because of electrically tunable focal length and controllable focal plane.

1. Introduction

Although two-dimensional (2D) images can provide a clear and colorful sense of visual perception, they cannot present information regarding differences in depth and disparity among the components of images. Therefore, three-dimensional (3D) images have attracted considerable attentions as they can provide more information about the surface of organisms and materials or other applications [1–3]. In general, the confocal microscopy is used to capture 3D images. However, this process consumes much time because of the mechanical movement [4,5]. For the application of capturing live specimens, this microscopy is not suitable. Thus, micro-lens arrays (MLAs) fixed between the object and the sensor have attracted much attention for microscopy because of the abilities of capturing different angular information without mechanical movement [6–9]. Typically, the MLAs include lenticular lens [10], active liquid crystal (LC) lenticular lens [11,12] and electric-field-driven LC (ELC) lens [13–15]. Compared with the lenticular lens arrays and active LC lens with fixed focal length, ELC lens with tunable focal length and their depth of field has been extensively applied in 3D display [16–19] and imaging systems [20–23].

Recently, LC lens with electrically tunable focal length is an active optical element without any mechanical movements and has become an alternative to traditional fixed focal length lens in the field of microscopy [23,24]. Because of excellent electro-optical properties of LC materials such as relatively large electrical and optical anisotropies, the LC molecules in the cell tend to be re-oriented in an electric field. Therefore, the rotation angles of LC molecules can be controlled remarkably by applying different operating voltages to the driven electrodes of LC cell. This electro-optical characteristic of LC materials can be used to construct particular micro-optical components. When an incident rays passes through the micro-optical components, the rays can be converged or diverged [22]. So far, several typical nematic LC materials have been employed to fabricate electrically tunable micro-lenses. As known, the first LC lens was constructed by Sato in 1979 [25]. Subsequently, Nose and Sato [26] also prepared a LC micro-lens with a hole-patterned electrode and an indium–tin-oxide (ITO) coated counter electrode to generate a non-uniform electric field. After that, many new electrode structures were proposed, such as the hole-patterned electrodes [13,27], multi-electrodes [28], ring electrodes [29,30], dual layer electrodes [23] and hexagonal electrodes [31,32].

In this paper, we propose a dual-layer electrode-driven liquid crystal (DELC) lens with tunable focal length and controllable focal plane. The top substrate of the novel DELC lens is coated with internal driven electrodes based on a dual-layer staggered structure in the cell, which permits the establishment of an alternative controllability. The proposed DELC lens can realize an electrically tunable focal length by changing the operating voltages. It can also realize a controllable functionality of focal plane by changing the driving method of the applied voltage to

---

* Corresponding authors.
E-mail addresses: xtzhou@fzu.edu.cn (X.T. Zhou), gtl@fzu.edu.cn (T.L. Guo).

https://doi.org/10.1016/j.optcom.2017.12.008
Received 19 September 2017; Received in revised form 1 December 2017; Accepted 3 December 2017
0030-4018/

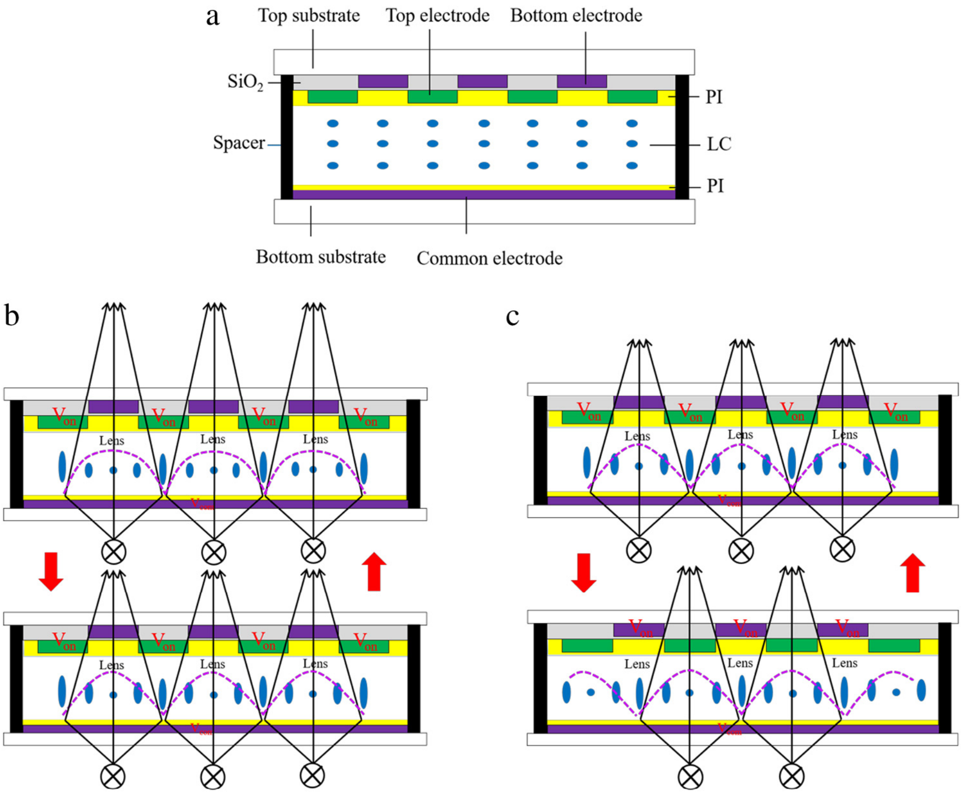

Fig. 1. (a) Structure and the basic principle of the DELC lens, (b) driving method of changing the operating voltage and the formation of DELC lens with electrically tunable focal length and (c) driving method of moving the position of driven electrode and the formation of DELC lens with controllable focal plane.

the next driven electrodes. Furthermore, the DELC lens requires only a very simple layout of driving circuit with a simple fabrication process.

2. Dual-layer electrode-driven LC lens

2.1. Structure and operating principles of DELC lens

To understand the working mechanism of the DELC lens, it is necessary to clarify the structure and the basic principle of the DELC lens. Fig. 1(a) presents the cross-section of the DELC lens with internal driven electrodes based on the dual-layer staggered structure in the cell. The DELC lens consists of an LC layer, a staggered driven electrodes, a common electrode, PI rubbing direction arrangement and glass substrates. The top electrodes and bottom electrodes are staggered and paralleled on the top substrate, and the adjacent electrodes are separated by a SiO_2 insulation layer. The driven electrodes have a uniform width. When an operating voltage was applied between the staggered driven electrodes and the common electrode to control the LC orientations, the LC lens worked as a cylindrical gradient-index lens. The rotation angle of the LC molecules continually changed and formed a DELC lens of different focal lengths by changing the operating voltage, as shown in Fig. 1(b). The DELC lens could realize the sub-pitch lenslet movements along the directions of driven electrodes by changing the driving method of the applied working voltage (V_{on}) to different driven electrodes, and a DELC lens with a controllable focal plane was realized, as shown in Fig. 1(c).

2.2. Simulation and design

In order to realize a controllable DELC lens, a commercial software (TechWiz.LCD.3D) was employed to simulate the distributions of rotation angle and potential in the cell. The 3D simulation model and cross sectional view of the DELC lens are presented in Fig. 2. The simulation model is composed of a bottom substrate and a top substrate, which are separated by a spacer with a diameter of 45 μm (cell gap). The lineal driven electrodes on the top substrate are fixed to be seven strips (three top electrodes and four bottom electrodes), and the width of the driven electrode was approximately 91.68 μm.

The LC director profile and electric field distribution within the cell were calculated by the commercial software TechWiz.LCD.3D, as shown in Fig. 3. When a high operating voltage was applied between the driven electrodes and common electrode, the direction of LC molecules could be affected by the electric field distribution. From the results, the refractive index distribution presents a gradient distribution, which is closer to the ideal parabolic curve. Fig. 3(a) shows that the electric field distribution is close to the ideal parabolic curve when the working voltage V_{on} was selectively applied to the 1st, 4th and 7th driven electrodes (State 1). When the position of the driven electrodes was moved to the next electrode, and the working voltage V_{on} was applied to the 2nd and 5th driven-electrodes (State 2), the electric field distribution of State 2 was consistent with that of State 1, as shown in Fig. 3(b). When the position of the driven electrodes was moved again and the working voltage V_{on} was applied to the 3th and 6th driven electrodes (State 3), the electric field distribution of State 3 in Fig. 3(c) was consistent with that of State 1 and State 2.

Fig. 3(d) presents the relationship between the potential distribution and the position of the driven electrodes in different driving methods. When the driving method was changed, and the working voltage V_{on} was applied to the next driven electrode, the potential distributions in State 1, State 2 and State 3 remained consistent. Fig. 3(e) shows the relationship between the rotation angle of LC molecules and the position of the driven electrodes in different states. The figure indicates that the rotation angle curve is close to the perfect parabolic curve near the driven electrode. The distributions of the rotation angle in State 1, State 2 and State 3 also remained consistent. Fig. 3(f) reveals the effective refractive index (n_{eff}) distribution of the LC lens structure at an operating voltage of 40 V. The refractive index distribution matched with the rotation angle of LC molecules.