Electrically Tunable Liquid Crystal Lens based on Zirconium Phosphate Nano Colloid

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Abstract- The nematic liquid crystals (LCs) have risen as a promising material for tunable lenses with high potentiality in the field of electro-optical applications, including display devices for augmented reality and virtual reality. However, several characteristic limitations of conventional LC materials such as polarization-dependency and short beam path length have brought about critical restrictions on actual applications of LC-based tunable lenses. Here, we report that concentration-controllable nano-colloidal dispersion can be a good candidate for functional materials for tunable lenses. Unlike usual LCs, the refractive index of colloids depends on the particle concentration in colloids, and using dielectrophoresis, we could manipulate the density distribution and consequently the refractive index profile, as well. Besides, the colloidal lens system can be devised to have a polarization-independent lens effect and a wide tuning range of positive to negative focal length using negative dielectrophoresis (n-DEP) and a two-dimensional (2D) α-ZrP nano colloid.

Keywords: Liquid crystals lens, 2d materials, Dielectrophoresis, Nano-colloid, Lyotropic liquid crystals

I. INTRODUCTION

An electrically tunable lens is a fascinating research topic having a high potentiality in display applications including virtual reality (VR) display and augmented reality (AR) displays, because they can directly control the focus or depth of displays without any mechanical motion or bulky system. Many researchers have developed lenses with tunable focal length in the last decades by utilizing various functional materials such as tunable plasmonic crystals, stimuli responsive hydrogels, and nematic liquid crystals (LCs) [1]. Among those lens materials, nematic LC has been regarded as the most promising candidate for the tunable lens, because it is simply achieved to electrically control the refractive index in nematic LC medium. However, LCs are optically anisotropic materials and are sensitive to the polarization of incident light [2]. As a result, only one direction of polarization works properly within LC medium, which results in the loss of one-half of the incident light. Several approaches to avoid the polarization-sensitive issues in LC lens have been proposed, but each of the avoidance techniques has its own limitation. Nonetheless, it is hard to find alternative materials to replace the polarization-sensitive nematic LCs in the tunable lens system.

In this study, we introduce a new material for the tunable lens, that is, a 2D nano colloid using exfoliated α-ZrP nanoparticles. Using the new material and system, we could successfully implement a polarization insensitive tunable lens. The refractive index profile in the colloidal medium is electrically controlled by manipulating the density distribution of ZrP particles by using negative dielectrophoresis (DEP). In the colloidal-based lens, the focal length can be continuously and reversibly controlled in a wide range from negative to positive values.

II. MATERIALS AND METHODS

Two dimensional, layered α-zirconium phosphate (α-ZrP, [Zr(HPO4)2·H2O)] nanoparticles were synthesized via a hydrothermal method. The nanoparticles were functionalized using a commercial polyoxyalkylene amine (Jeffamine ® M1000), and we obtained a good colloidal α-ZrP colloidal mixture in N, N-dimethylformamide (DMF) solvent. The FESEM image (left image in fig. 1a) revealed that the stratified nature of the obtained α-ZrP nano particles with an irregular hexagonal shape. Then, another α-ZrP colloidal mixture was prepared by introducing an intensive exfoliation process to the functionalized α-ZrP mixture using ultrasonication within the Jeffamine M1000 mixture. Although the FESEM images in the right of fig. 1a does not clearly identify the monolayered particles due to the extremely thin thickness, it is well discernible that the exfoliation process diminishes the particle thickness dramatically. The exfoliated samples also exhibit a clear LC phase under the cross polarizers, as shown in fig. 1b.

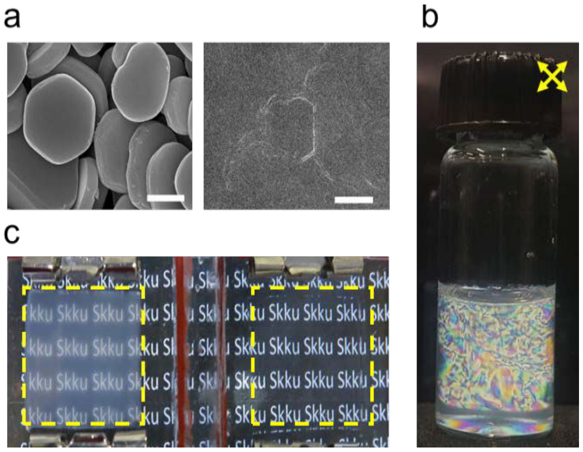

Fig. 1 (a) The field emission scanning electron microscopy images (FESEM) of 2D, α-ZrP nano particles before (left) and after the exfoliation (right), Scale bars, 1µm. (b) Liquid crystalline phase behavior of the exfoliated colloid. (c) Visual representation of the optical transparency of the non-exfoliated (left) and exfoliated(right) nano colloids; Yellow dotted line indicates the boundary of the cell.

III. RESULTS AND DISCUSSION

Optical transparency of a material is a fundamental requirement to allow the optical usage in optoelectronic devices. Transparency of the synthesized two α-ZrP colloidal mixtures were investigated by direct observing 2-mm-thick cells containing each colloidal mixture. Fig. 1c shows the comparison of the optical transparency of the non-exfoliated and exfoliated α-ZrP nano colloids. Here we performed the tunable lens experiment using the exfoliated α-ZrP colloidal mixture in order to obtain a clear lens. The cells were made by utilizing two patterned indium tin oxide (ITO) electrodes. For the positive lens, a circular hole (diameter of 6 mm) was etched from the middle of the ITO substrate and a reversed shaped electrode was utilized for the negative lens as illustrated in top and bottom images in fig. 2a, respectively. A PDMS spacer was used to maintain the gap of 2 mm between the top and bottom substrates and α-ZrP sample of 1.18 wt.% was injected to the fabricated cells, and 10 kHz square wave electric field was applied. Both lens effects were visually observed placing each cell in between a printed paper with text pattern and a camera (as shown in fig. 2b) as the input voltage increases from 0 to 150V. Based on the electrode design, prepared cells exhibit positive and negative lens effect as well discernible in the photographs in Fig. 2c

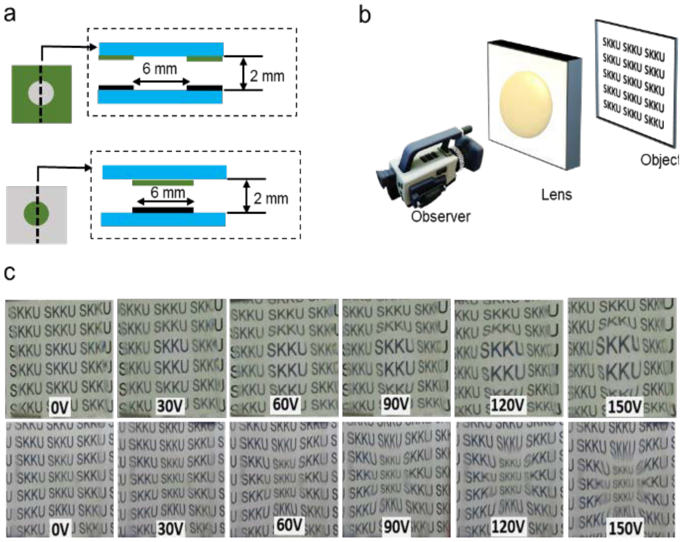

Fig. 2 (a) Cross-sectional view of the lens cell structures with (top) positive and (bottom) negative focal lengths, respectively. (b) Schematic diagram of the experimental setup for the tunable lens experiment. (c) Positive (top set of images) and negative (bottom set of images) lens effect obtained in the nano colloidal tunable lens, at various applied voltages.

DEP is an excellent tool for manipulating electrically neutral and charged particles when subjected to a non-uniform electric field. Ignoring higher-order effects of polarization, the DEP force exerts on a spherical particle with volume V, under an electric field E, can be approximated as,

$$\vec{F}_{DEP} = \frac{1}{2}\varepsilon_m V \cdot \mathrm{Re}[K] \cdot \nabla(\vec{E} \bullet \vec{E})$$

Here, K is the polarization factor which can be further simplify by using the complex permittivity of particle (εp) and suspended medium (εm) according to the Equation 2,

$$K = \frac{3(\varepsilon_p^* - \varepsilon_m^*)}{\varepsilon_p^* + 2\varepsilon_m^*} \qquad (2)$$

It can be seen from Eq. 1, depending on the sign of the Re[k] factor, the DEP force propels particles either towards the E-field maxima (positive DEP) or minima (negative DEP). The polarization factor was measured to be negative in the operating frequency range by utilizing a mixture of 1.2 wt.% α-ZrP colloid in DMF. The E-field distributions inside the both cells are highly non-uniform (essentially edge of the electrodes) and as consequence nano particles experience a DEP force, in which they either migrate toward (positive lens) or away (negative lens) from the center. This particle movement leads to modify the nanoparticles concentration in the medium and modify the refractive index distribution accordingly. The corresponding focal lengths of the positive and negative lens was further measured as 7.5 cm and -11.2 cm at 150V, respectively. In addition, field induced birefringence (Δn) of the α-ZrP nano colloid exhibits a relatively low value ($\sim 4.0 \times 10^{-5}$) referring to the nematic LC's (0.05−0.2) and therefore it can simply ignore the polarization dependence property, which is one of the merits in our system.

IV. CONCLUSIONS

We have demonstrated a polarization independent and electrically tunable lenses with positive and negative focal lengths by incorporating 2D α-ZrP nano-colloidal liquid crystals. The effective refractive index profile was altered without any mechanical movements. The advantage of the devices is a wide focal-length tuning range, a simple cell and electrode structures, no use of polarizer, and rather thick cell thickness. These types of systems can be highly useful in the lens systems of AR and VR display.

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