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Further study of optical homogeneous effects in nanoparticle embedded liquid-crystal devices☆

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A B S T R A C T

Herein, we report the enhancement of electro-optical performances of nanoparticle embedded liquid-crystal devices in the laser speckle pattern reduction, enhancement of viewing angle, and that of color gamut by doping the nano-particles (NPs) of PγCyclodixtrin-ZrO_2 (Shiraishi lab) and Aerosil R-812 (EVONIK) into the liquid crystal devices. This report will be done through updating of previous work in particular giving physical modeling based on Rayleigh–Gans optical scattering theory and effect of the rising of the effective temperature called Kobayashi temperature due to the existence of NPs in an LC medium and by conducting simulations.

1. Introduction

In a previous paper, we reported that the doping of nanoparticles into liquid-crystal electro-optical devices brings enhancements of their characteristics such as high-speed response, wide viewing angle, large color gamut reaching 140% of NTSC specification, implementation of field sequential color LCDs, and optical homogenizing effect including laser speckle patter reduction [1–6]. Herein in this paper we report physical explanations of these effects by updating previous work.

2. Experimental

2.1. Materials

(1) Nematic liquid crystal: NTN-02(DIC), $n_e = 1.625$, $n_o = 1.499$, $\Delta\varepsilon = 4.92$

(2) Electrically controllable birefringence (ECB) cells: cell gap of 13 μm, with and without doping NPs of PγCyD-ZrO_2 (Shiraishi lab) [6].

(3) Narrow gap field sequential (color-filter-less) twisted nematic (NTN) modules (10 cm × 10 cm, 100 × 100 pixels) (OKAYA) [5] with and without doping NPs of Aerosil R-812 (EVONIK) and ECB-cells with PγCyD-ZrO_2.

(4) Nanoparticles: A) PγCyD-ZrO_2 (Shiraishi lab) NP size is 7.2 nm and n = 2.2, doped quantity was 0.075 wt% and mean distance between NPs is 40 nm. B) Aerosil R-182 (EVONIK) 5 PNs of SiO_2, n = 1.46 are aggregated, where each size of NP is 7 nm and size of this ensemble to gather with ligand molecules is 40 nm, doped quantity was 0.1 wt%, mean distance between the nanoparticle systems is 140 nm. Usually Aerosil R-182 has the size of 400 nm; in our research, we got 40 nm -size NP system from those with 100 nm-size in the following way: we doped original NPs into NLC (NTN-02) to gather with a chiral dopant having the pitch of 12 μm and the bottle containing this mixture was subjected to a sonication for 2 h. EM micro-photographs of a freeze break technique are shown in Fig. 1(a) before the sonication and (b); after the sonication demonstrating successful getting of NP system with 40 nms size in which there exist seven silica NPs. Those TEM treatments were done by Tokuyama Corp.

3. Experimental results and considerations

3.1. Laser speckle reduction

For the observation of optical transmitted pattern through ECB cells with and without doping NPs of PγCyD-ZrO_2, we used a laser with

☆ Retrospection of Professor Yuriy Reznikov and our condolences: We remember your active and earnest figure when you gave a talk on the physics of magnetic nanoparticles; you stay in our hearts forever. We express our sincerest condolences.

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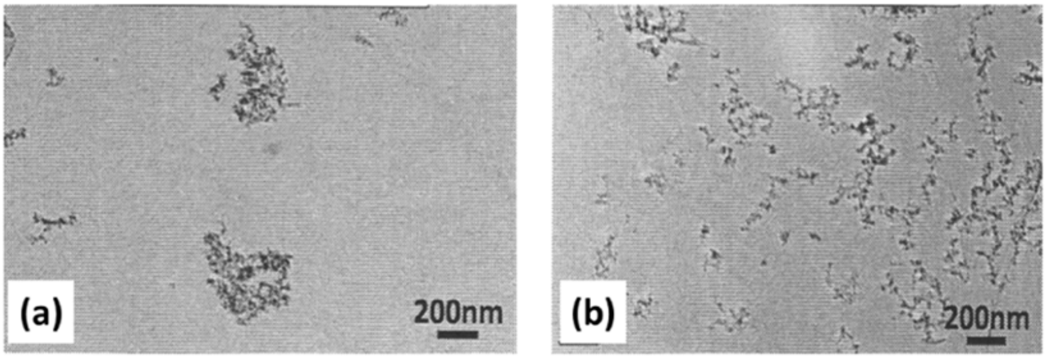

Fig. 1. TEM photographs: (a) before sonication and (b) after sonication (©SPIE).

wavelength 488 nm (LGK7872M LASOS). A white screen was placed at a distance of 30 m from the cell. Fig. 2 demonstrates the scattering patterns projected on a screen of an Argon laser beam passing through the ECB cells without NPs (Fig. 2(a)) and with NPs (Fig. 2(b)). The laser speckles and some bright crosses are visible on the screen as seen in Fig. 2(a). The bright crosses are the diffraction from the periodic structure on the substrates of the ECB cell. By contrast, the speckles are smooth out after passing through the NP-embedded liquid crystal (LC) cell as seen in Fig. 2(b); the same is true for the stripes. There is no external voltage applied on the LC cell during observation, which indicates that it is zero-power consumption laser speckle reduction device. The similar results were reported by Furue et al. [5] with the NPs of fumed silica NPs Aerosil R-812.

The benefit of using PγCyD-ZrO2 NP is that there is large refractive index difference between NPs and LC host. The scattering intensity increases as the refractive index between NP and LC host is large, where the necessary quantity of doped NPs was only 0.075 wt%.

The reduction of speckle pattern and crosses may be attributed to the optical scattering by the NPs and thus de-coherence occurs for passing light though the NP embedded ECB cell, where the size of NP is much smaller than optical wave length. This kind of optical scattering will be analyzed with Rayleigh–Gans criteria [7,8,9] such that:

$$2\,ka|m-1|\ll 1$$

where k is the wave number for light with wavelength λ propagates in a medium with the refractive index ratio m between $n_{nanoparticle}$ and n_{medium}, and $k = 2\pi/\lambda = 2\pi n_{medium}/\lambda_{vac}$, and a is the radius of the NP. In this system, the diameter of NP is ~7 nm and the wavelength of light is 488 nm, which satisfy Rayleigh–Gans criteria. The mechanism of laser speckle reduction with nanoparticles is illustrated in Fig. 3. We use one-dimensional NP array as example to explain the laser speckle reduction contributed by the scattering effect of nanoparticles. Light (yellow arrows in Fig. 3) shines on the nanoparticles from the left-hand side, which creates a forward scattering pattern on the right-hand side. The projection of scattering pattern from each nanoparticle has Gaussian-like intensity distribution. The width between the 50% intensity location is defined as full width half maximum (FWHM). The distribution of nanoparticles and scattering pattern are critical for laser speckle reduction. In order to smooth out the speckles, the FWHM has to be larger than the speckle periodicity $\sigma \approx 1.2\frac{\lambda D}{D_{laser}}$, where D is the observation distance as denoted in Fig. 3, λ is the wavelength of incident light, and D_{laser} is the diameter of the laser spot [9]. The mean nanoparticle distance has to be smaller than FWHM so that the scattering pattern of nanoparticles does not create another speckle-like intensity distribution. In order to have minimized intensity loss, the scattering has to be from multiple nanoparticles.

In the experiment, the FWHM of the scattering pattern from single NP on the screen calculated by Rayleigh–Gans scattering, which is ~46.5 m, is larger than the average distance between NPs that is about 40 nm. From calculation, the laser speckle periodicity from the laser, which is ~17.6 mm, is smaller than the FWHM of the scattering pattern of the NP in the system [10]. The number of NPs covered within the laser spot is ~10^{10}. Therefore, the scattering can reduce the laser speckle efficiently without losing the light intensity. We compare scattering effect between NP of PγCyD-ZrO_2 and that of Aerosil R-812. The result was that PγCyD-ZrO_2 shows efficient optical scattering effect even though amount of doping of NPs is 0.074 wt%; by contrast Aerosil R-812 needed doping of 30 wt% and needed for applying electric fields [6]. Benefit of using PγCyD-ZrO_2 with n = 2.6 is that there is a large refractive index discrepancy between NPs and LC host with n = 1.625, whereas the refractive index of silica is n = 1.46 bringing a weak optical scattering. A

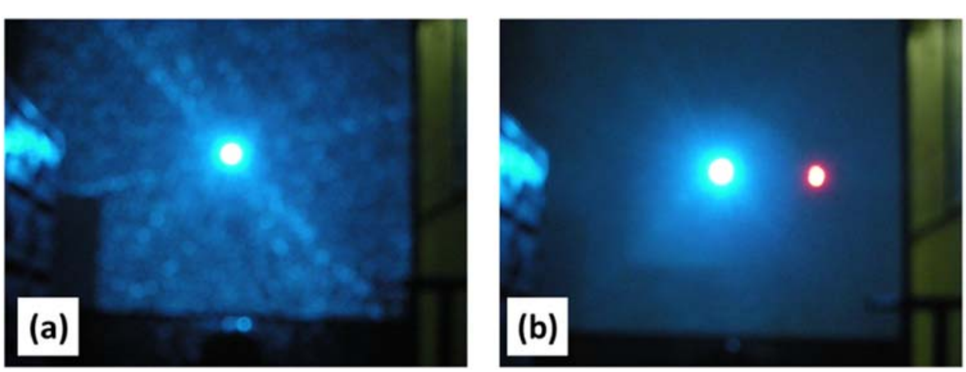

Fig. 2. Optical patterns projected on a screen of an Argon laser beam passing through ECB cells: (a) without NPs and (b) with NP doped (©SPIE).

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