

Highly Transparent Photoalignment Material for Fabricating Holographic Optical Elements

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Abstract:

The optical properties of a new photoalignment material RN-4942 and its applications in fabricating passive liquid crystal devices, including Pancharatnam-Berry phase optical elements and polarization volume holograms for AR/VR systems are investigated. Compared to conventional azo-dye alignment materials, RN-4942 offers a ~1000x higher exposure sensitivity, a faster fabrication process, lower dosage requirements, and greater humidity resistance during the fabrication process.

Author Keywords

Photoalignment material, Pancharatnam-Berry phase optical elements, polarization volume holograms

1. Introduction

Liquid crystals (LCs) play an important role in the display industry, where the quality of their initial alignment is key to fabricating holographic optical elements (HOEs) and high-performance displays (1,2). Controlling the LC alignment involves the use of alignment material with unique properties and fabrication methods. The most conventional alignment material used for mass production of liquid crystal displays is polyimide (PI) (3). However, the polyimide fabrication process requires mechanical rubbing, which presents challenges such as creating static charges and scratches on the surface. Therefore, to achieve a high alignment quality, and high-performance augmented and virtual reality (AR/VR) microdisplays, photoalignment is commonly used (4,5).

Photoalignment is a non-contact process, that induces anisotropy in an alignment material by irradiating it with polarized light within the material's absorption band (6-10). There are generally three types of photoalignment methods including photodegradation (11,12), Photoisomerization (13-16) and photocrosslinking (17-19). Photoisomerization occurs in azo-dye-based alignment materials, which are among the most well-researched types of photoalignment materials. Some commonly used azo-dye-based photoalignment materials are Brilliant Yellow (BY), Mordant Yellow, and SD-1 (20). While Azo dye-based photoalignment materials offer uniform alignment, high thermal stability and no charge generation or damage to the system, they also are re-writable alignment layers, which can limit their practical applications in AR/VR displays.

In this manuscript, we report several outstanding features of RN-4942, a non-rewritable planar liquid crystalline alignment material with a photosensitive sidechain developed by Nissan Chemical Corp. (21) and its application in polarization holography. This material exhibits high sensitivity to UV light and a much shorter exposure time (2 seconds for 8.5 mJ/cm²), which greatly enhances the fabrication stability by reducing environmental disturbances. Therefore, it achieves perfect and precise

alignment for fabricating passive liquid crystal holographic elements for AR/VR displays.

In Section. 2, we first demonstrate the optical properties and fabrication process of RN-4942 and then highlight its advantages over BY azo-dye-based photoalignment material, which is commonly used in scientific research. In Section. 3, we will discuss the application and performance of RN-4942 in fabricating passive LC devices such as Pancharatnam-Berry Optical Elements (PBOEs) (22-24) such as PB gratings, PB lenses and microlens arrays, polarization volume hologram grating (PVGs) as AR combiners (25, 26).

2. Properties and fabrication of RN-4942

According to the data provided by Nissan chemicals corp., as shown in Figure. 1, peak absorption of RN-4942 occurs at $\lambda \approx 320$ nm and it exhibits high transparency in the visible region.

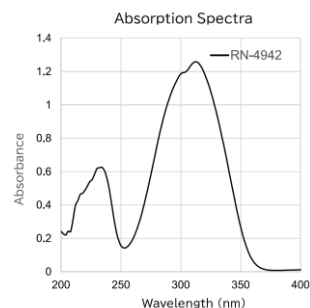


Figure 1. Absorption spectra of RN-4942.

In comparison, SD-1 and BY exhibit peak absorptions at 360 nm and 432 nm, respectively (8,15). Unlike RN-4942, BY-based alignment material absorbs blue light resulting in a yellow undertone in the fabricated HOEs, which can be unpleasant for near-eye head-mount display users.

The general fabrication process of passive liquid crystal HOEs using RN-4942 as the photoalignment layer is as follows:

1. To prepare the RN-4942 alignment layer, first a 0.5-mm glass substrate was cleaned with ethanol alcohol and treated with UV-ozone for 5 minutes to remove organic residues.
2. The substrate was then spin-coated with a deposited RN-4942 solution at 200 rpm for 5 seconds rise time and 2000 rpm for 25 seconds.
3. Pre-baking was performed at 70°C for 2 minutes on a hotplate.
4. The sample was exposed to UV light (365 nm) in a holography set up of 8.5 mJ/cm² for 2 seconds.
5. Post-baking was carried out at 140°C in 10 minutes to ensure fixed alignment of RN-4942.
6. After preparing the spatially varying polarization-patterned alignment layer, the sample was coated by a

thin layer of nematic liquid crystals (e.g., RM-257) or chiral liquid crystal (CLC)

7. Finally, the sample was cured under UV light for 2 minutes.

In this paper, two different RN-4942 solution concentrations are studied: 1) 0.5 wt.% RN-4942 solution in N-Methyl-2-Pyrrolidone (NMP, 79.5 wt.%) and Butyl Cellosolve (BCS, 20 wt.%) solvent, and 2) 6 wt.% RN-4942 solution in N-Methyl-2-Pyrrolidone (NMP, 74 wt.%) and Butyl Cellosolve (BCS, 20 wt.%) solvent.

The process before and after photoalignment exposure was performed in a laboratory at a temperature of 22°C and a relative humidity (RH) of 20–45%. The sample was then exposed under laboratory conditions of 17°C and 51% RH. Table 1 summarizes a comparison of the fabrication processes of BY and RN-4942 photoalignment materials.

Table 1. BY vs RN-4942 photoalignment material

photoalignment material	Exposure light	Exposure dosage	Exposure time in our lab	Sensitivity to high humidity	Re-writability
BY	488 nm	2-5 J/cm ²	90s	Yes	Yes
RN-4942	355 nm	3.5-8.5 mJ/cm ²	2s	Not observed	No

Based on the dosage and exposure time shown in Table 1, it is evident that RN-4942 is three orders of magnitude more sensitive to the exposure light than BY. Additionally, its short exposure time ensures that the holography process is unaffected by the environmental disturbances, resulting in an excellent alignment quality. Furthermore, in contrast to BY, which aligns best at 20%–28% RH (14) and is highly sensitive to the environmental humidity over 40% during fabrication (27), our observations indicate that the alignment quality of RN-4942 is not affected by the humidity or temperature alterations.

3. Applications of RN-4942 alignment layer

In this section, we provide several applications and performances of the RN-4942 photoalignment material in liquid crystal polarization holography.

3.1. PB Grating

A Mach Zender interferometer was used to fabricate the PB grating. As shown in Figure 2, linear polarized light (LP) from a UV laser (355 nm) passes through the first polarization beam splitter (PBS1). The beam separates into two orthogonal linear light beams, which are reflected by mirrors and re-enters a second PBS mounted on a mobile stage (PBS2), moving in the X-Y plane which allows precise control of the interference angle.

The beams will then interfere after passing through a quarter wave plate (QWP). The interference of these two orthogonal circular light beams (CP) will form a spatially varying polarization pattern on the RN-4942 photoalignment material (28). Lastly, the sample is coated by a 1:4 and then 1:5 reactive mesogenic liquid crystal (RM-257) to toluene solution to achieve half wave retarder thickness for the designed wavelength (532 nm).

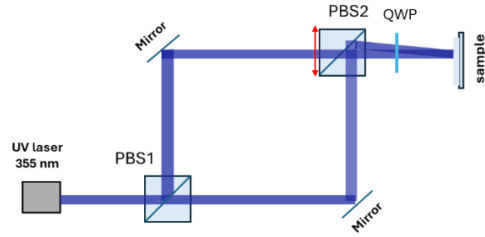


Figure 2. Holographic exposure system of PB grating.

The rotating director direction of the liquid crystal in contact with the grating pattern of RN-4942 alignment layer is illustrated in Figure 3a. The resulting BP grating (as shown in Figure 3b) has a grating pitch of 5 μm under a 10x magnification of Olympus BX51 microscope. Both PB gratings, fabricated with 0.5 wt.% and 6 wt.% RN-4942 solutions, exhibit 99.7% diffraction efficiency, demonstrating their high performance and the excellent alignment enabled by RN-4942.

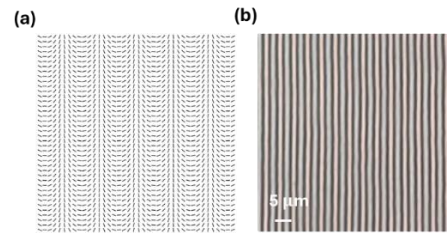


Figure 3. a) PB grating LC director pattern. b) 5 μm pitch PB grating image under a microscope.

The interference angle (θ), which determines the pitch size (Λ) of the PB grating, is calculated using the following equation:

$$\Lambda = \frac{\lambda}{2\sin(\theta)} \quad (1)$$

In this paper, the wavelength (λ) is 355 nm and to achieve a grating pitch of 5 μm, the interference angle θ was set to 2.03°. To test the performance of the fabricated PB grating as demonstrated in Figure 4, we sent an expanded linear light beam of a green laser 532 nm through the PB grating. It acts as a beam splitter, diffracting the right-hand circular light (RCP) to the 1 order and left-hand circular light (LCP) to the -1 order with the diffraction angles of 6.1° and -6.1°, respectively, according to the grating equation:

$$\Lambda x \cdot \sin(\theta) = \lambda \quad (2)$$

In Eq. (2), θ is the diffraction angle, λ is the wavelength of the incident light (in this case, 532 nm) and Λx is the grating (pitch in this case, 5 μm).



Figure 4. Experimental system for testing the PB grating.

3.2. PB Lens/mini-Lens Array

The holography exposure set up for PB lens/lens-array is similar to the PB grating holography system, with the key difference being that the reference phase object is placed on the recording beam path of the two-beam interferometer.

In this experiment, by incorporating a 100 mm focal length lens in a Mach-Zehnder interferometer (Figure. 6) a parabolic lens phase profile was relayed onto RN-4942. The sample was then coated with 1:5 and 1:4 RM to oluene solutions to satisfy the half-wave condition for the PB lens at a 532 nm wavelength. This method can also be used for fabricating mini-lens arrays.

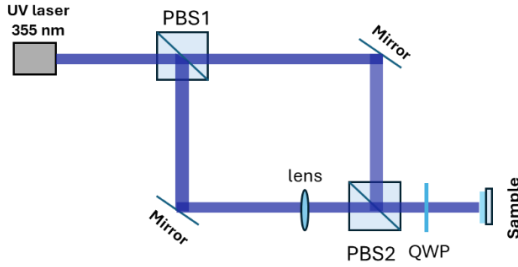


Figure. 5. Holographic exposure system for PB lens.

The liquid crystal director distribution on the RN-4942 lens pattern is demonstrated in Figure. 7a and Figure. 7b shows an image of a fabricated PB lens profile under 10x magnification of Olympus BX51.

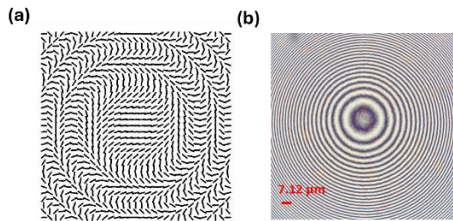


Figure. 6. a) LC director distribution in a PB lens. b) Observed PB lens phase profile under an optical microscope.

To evaluate the performance of the fabricated optical element, the PB lens with focal length of 66.7 mm was illuminated by expanded linear light from a 532 nm laser. As shown in Figure. 8, this lens will focus RCP light at the 66.7 mm focal point and defocus LCP light to an imaginary focal point 66.7 mm behind the PB. Measured Diffraction efficiency of the PB lenses made with 0.5 wt.% and 6 wt.% concentrations is 99.5%.

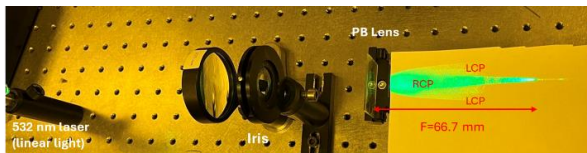


Figure. 7. Experimental system for testing the PB lens.

3.3. Short pitch r-PVG for AR Waveguides

The hologram grating exposure system used to fabricate a reflective short pitch polarization volume hologram grating (r-PVG) is shown in Figure. 9. In this setup linear polarized light from a UV laser (355 nm) passes through a QWP and converts the LP light to CP light. CP light then passes through a PBS, separating the CP beam into two orthogonal LP beams. In each arm of the interferometer the LP is reflected by the mirrors and passes through additional QWPs.

A sinusoidal linear polarization pattern is formed on the RN-4942 alignment layer due to the interference of these two orthogonal circular light beams. The Sample is then coated by a CLC solution composed of a mixture of 1:2.5 CLC (with 2% S5011(left-hand helix structure), 3% Irg, and 95% RM-257) to toluene solution.

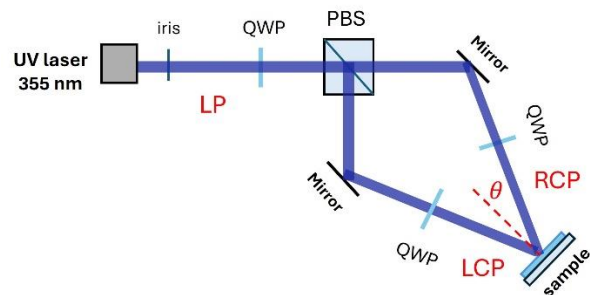


Figure. 8. Holographic exposure system for r-PVG.

By using Eq. 1 the interference angle (θ) of 26° was obtained to be used to fabricate the 400 nm pitch r-PVG at 532 nm. To test that, LCP was sent to the left-hand PVG (LH-PVG), which reflects light with the same handedness as the CLC's helical structure, in this case LCP (Figure. 10). We used a 6% RN-4942 solution, to fabricate r-PVGs that can be used as the input and output coupler of a waveguide combiner. Depending on the application the diffraction efficiency of r-PVG can be controlled by the thickness of the CLC layer.

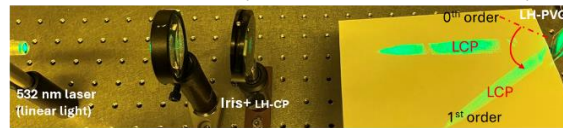


Figure. 9. Experimental system for testing the r-PVG.

We used a 6 wt.% RN-4942 solution, to fabricate r-PVGs with detail that can be used as the input and output coupler of a waveguide combiner (26). Depending on the application the diffraction efficiency of r-PVG can be controlled by the thickness of the CLC layer.

4. Conclusion

RN-4942 is a highly sensitive liquid crystal photoalignment material with approximately 1000 times greater sensitivity to exposure light than azo-dye-based materials like BY and SD-1, enabling a faster exposure time of 2 seconds. Consequently, it also offers strong resistance to environmental disturbances, such as temperature fluctuations, humidity changes and vibrations, ensuring a

stable fabrication process. Additionally, fabricating high-performance passive HOEs, including PB gratings, PB lenses (with ~99% diffraction efficiency), and reflective PVGs with RN-4942, makes it a promising candidate for mass production of advanced planar optical components used in AR/VR applications.

5. References

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