

Colorless photoalignment material for fabricating liquid crystal holographic optical elements

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Abstract: The optical properties of a new colorless photoalignment material, RN-4942, its fabrication stability, and applications in fabricating passive liquid crystal devices, including Pancharatnam-Berry phase optical elements and polarization volume holograms for augmented reality (AR) and virtual reality (VR) displays, are studied. Compared to conventional alignment materials, RN-4942 offers a ~1000x higher exposure sensitivity, faster fabrication process, lower dosage requirements, and greater humidity resistance during the patterned-alignment fabrication using a holographic exposure setup, ensuring a much better alignment stability. In addition, RN-4942-based devices exhibit high thermal, temporal, and photo stabilities, making them exceptional candidates for AR/VR display applications.

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1. Introduction

Liquid crystals (LCs) are birefringent materials that are highly responsive to the changes of the surrounding environment. When in contact with an alignment layer, the LC molecules align with respect to the physical structure or chemical properties of this material at the LC/alignment layer interface [1]. As a result of the intermolecular interactions between LC molecules, the self-alignment is maintained through the bulk of the LC layer. This property plays an important role in the liquid crystal display (LCD) industry, where the quality of initial alignment is key to fabricating high-performance LC devices, holographic optical elements (HOEs), and advanced displays [2]. Controlling LC alignment involves the use of specialized alignment layers, each with unique properties and fabrication methods. Conventional alignment material used for LCD mass production is polyimide [3]. However, the polyimide fabrication process requires mechanical rubbing, which presents challenges such as creating static charge, scratches on the surface, and nonuniform alignment layers.

Therefore, to achieve high performance and high-resolution density augmented reality (AR) and virtual reality (VR) microdisplays, photoalignment materials are widely used [4,5]. Photoalignment is a noncontact process of inducing anisotropy in an alignment material by illuminating it with a polarized or collimated light within the material's absorption band [6–10]. For successful integration into commercial LC devices, the photoalignment layer must exhibit high thermal, temporal, and photo stabilities, i.e., the alignment layer should maintain stable alignment at high temperatures, over time and under UV or visible light exposure during and after the fabrication process.

Generally, there are three well-known types of photoalignment processes: photodegradation [11,12], photoisomerization [13–16], and photocrosslinking [17–19]. Photodegradation is an irreversible chemical reaction in which the alignment materials, such as polyimides that are aligned parallel to the incident light polarization, are broken down into smaller oligomers by absorbing polarized light, thereby aligning LC molecules perpendicular to the light polarization direction. However, this process can create excessive chemical compounds that may contaminate

the LC material, affecting its electro-optic properties, creating defects, and leading to low alignment quality.

For the photoisomerization-type material, in response to the absorbed polarized light, the molecules reorient and undergo cis-trans isomerization. Photoisomerization is a reversible process. Common azo-dye-based photoalignment materials such as Brilliant Yellow (BY), Mordant Yellow, and sulfuric dye (SD-1) will experience photoisomerization [20], in which they reorient orthogonally to the electric field of the incident polarized light. While azobenzene based alignment layers offer uniform alignment, good alignment performance, and do not generate charge or cause damage to the system, they have low thermal stability [10] and are also optically re-writeable because no chemical changes occur in these materials during the fabrication process, which can affect the long-term photostability and limit their practical applications in AR/VR displays.

The third-type photoalignment process is photo-crosslinking, in which cinnamate, chalcone and coumarin are commonly utilized as photoreactive groups. In this process, exposure to the irradiated light induces nonreversible chemical reaction which creates covalent bonds between photopolymer chains, the alignment will be permanent and not rewritable. One wellstudied crosslinking type material is polyvinyl cinnamate (PVCN) which demonstrates high photosensitivity. However, due to its amorphous polymer nature, PVCN shows a low alignment efficiency for reactive mesogen (RM). It also exhibits low thermal stability for temperatures close to $100^{\circ}C$, which can be improved by employing the polyimide in the material. Chalcone based alignment, although highly photosensitive, provides inadequate alignment performance. Lastly, photoalignment using Coumarin as the photoreactive side chain offers good alignment quality but its photosensitivity needs improvement [10]. In summary, a photoalignment material with exceptional photosensitivity, high temperature resistance, and long-time stability are highly desirable for the display industry.

In this paper, we report several notable features of a photoalignment material, designated as RN-4942, developed by Nissan Chemicals Corp. RN-4942 contains a photosensitive side-chain polymer exhibiting liquid crystallinity within a specific temperature range [21] that photo-aligns through a cross-linking, non-reversible chemical reaction parallel to the polarization of the incident UV light. By baking and the curing process, the aligned RN-4942 sample will become very robust and not rewriteable. This material exhibits high sensitivity to the exposure light and requires a very small dosage (5-10 mJ/cm²), which greatly enhances the fabrication stability by reducing environmental disturbances. Therefore, it can achieve precise alignment for fabricating passive LC holographic elements (HOEs) for AR and VR displays.

Holography is the process of recording the interference pattern between a reference beam and an object beam and subsequently regenerating the recorded object beam's wavefront through the hologram with light. There are two methods for generating HOEs: intensity holography and polarization holography. Polarization holography is performed by the interference between two collimated beams with orthogonal polarization states: right-hand circularly polarized (RCP) light and left-hand circularly polarized (LCP) light. This holography method is widely used to fabricate the HOEs, including Pancharatnam-Berry phase optical elements (PBOEs) and polarization volume holograms (PVHs) [4].

PBOEs have been demonstrated by nanostructured materials [22], by spatially varying LC alignment through micro-rubbing process [23], or by optically aligning a LC alignment material through the control of the exposure field's polarization state. One mechanism by which a polarization state across a field may be spatially controlled is by polarization holography [24,25]. Two types of PBOEs: PB grating and PB lens, have found widespread applications. For example, a switchable-focus PB lens can be used in VR for creating multiple focal depths to mitigate the longstanding vergence-accommodation conflict [26]. Other useful applications of PBOEs include ultracompact optical systems and polarization-multiplexing optical systems.

The polarization volume hologram is a polarization-dependent tilted Bragg reflector [27]. The polarization-dependent response and ability to deflect a field at a very large angle have enabled the device's implementation as an input coupler in a waveguide-based AR glass, doubling the optical efficiency and brightness uniformity [28]. They can also be used as ultra-fast f/# off-axis lenses that can be used in a Maxwellian view system [29–31]. The requirement for a holographic grating to be used as an input/output coupler of an AR waveguide or as a fast f/# off-axis lens is a locally sub-micron grating pitch. A photoalignment material must be patterned with the sub-micron detail of a continuously rotating alignment, which completes a 180° rotation over a sub-micron distance (typically a 300 nm–450 nm pitch for waveguides).

In this paper, we first investigate the optical properties and fabrication process of RN-4942 alignment material in Sec. 2 and provide a comparison with BY azo-dye-based alignment materials, which are a common photoalignment material used in scientific research. Next, on Sec. 3, we explore the great potential and performance of RN-4942 photoalignment layer in fabricating passive LC devices, such PB gratings, PB lenses and lens arrays, reflective PVH gratings for AR waveguide, and reflective off-axis PVH lenses for AR optical combiners.

2. Fabrication process of RN-4942

The Nissan SUNEVER RN-4942 is a non-rewritable photoalignment material that offers liquid crystalline properties and fabrication stability compared to conventional photoalignment material used in the display industry. Figure 1(a) shows the absorption spectrum of RN-4942 within the 250 nm to 400 nm wavelength range. Its peak absorption occurs at $\lambda \approx 320$ nm and it is highly transparent in the visible region. Thus, a UV laser with a wavelength of 355 nm which is within the absorption band, is used in the holographic optical exposure system. In comparison, according to Fig. 1(b), SD-1 and BY exhibit peak absorption at 360 nm and 432 nm, respectively, and their absorption tail extends to the visible region [8,15]. Unlike RN-4942, BY-based alignment layer absorbs the light in the blue range, so the alignment layer of the fabricated HOEs shows a yellow tint, which can affect the users viewing experience if the fabricated device is used in the near-eye AR/VR displays.



Fig. 1. Absorption spectra of: (a) RN-4942 and (b) SD-1 and BY [redrawn from [15]].

The fabrication procedure of passive liquid crystal holographic elements with RN-4942 photoalignment layer is described as follows. As presented in Fig. 2, the first step is to prepare a substrate. In experiment, a 0.5-mm glass slide was cleaned by applying ethanol alcohol and treated with UV-ozone for 5 minutes to remove possible organic residues, which helps RN-4942 adhere better to the glass slide. Next, RN-4942 solution was deposited onto the prepared substrate and then spin-coated at 200 rpm for 5 seconds and 2000rpm for 25 seconds. Drying was



performed by pre-backing the sample at 70°C for 2 minutes on a hotplate. Afterwards, the sample was exposed to UV light (λ =355 nm and 8.5 mJ/cm²) in a holography setup for 2 seconds.



Fig. 2. Flowchart of the RN-4942 fabrication process.

RN-4942 is required to be post-baked at a temperature between 130 °C to 150 °C for 5 to 10 minutes within its nematic temperature range. Post-baking the patterned RN-4942 sample at 140°C for 10 minutes enhances the photoinduced anisotropy and alignment controllability by promoting self-assembly within the alignment layer in the nematic phase [19,21]. After preparing the spatially varying patterned alignment layer, the sample was overcoated with a thin reactive mesogen liquid crystal polymer (e.g., RM257) or chiral liquid crystal (CLC) and then cured under UV light for 2 minutes. Each vile of RM and CLC solutions were filtered with a 0.22 μ m filter to remove any remaining solid particles and achieve a homogeneous solution.

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. All fabrication steps except UV exposure, were performed in a laboratory environment at a 22°C temperature and 20-45% relative humidity. The samples were then placed in the holography setup in a laboratory with a temperature of 17°C and 51% relative humidity. The sample was transferred between these laboratories in a covered sample holder to prevent light exposure.

To test the thermal, temporal, and photo stabilities of RN-4942 photoalignment layer, following the exposure and post-bake steps, prior to reactive mesogen (RM) coating, a series of controlled experiments were conducted. A total of eight Panchratnam-Berry phase lenses (PBLs) were fabricated using the 6 wt.% RN-4942 alignment material and were post-baked. One of the exposed and post-baked samples (S1) was immediately coated with RM257 and served as the reference sample for all subsequent measurements. Three PBLs were subjected to various temperatures by being placed on hotplates at temperatures of 50 °C (S2), 70 °C (S3), and 100 °C (S4) for one hour, respectively. Each sample was then coated with RM257 and cured under a UV lamp. The diffraction efficiency of each sample was measured by using a spectrometer. The diffraction efficiencies of samples S2, S3, and S4 were approximately the same as the reference sample within $\pm 1\%$, which shows high thermal stability.

To evaluate the long-term stability under ambient conditions, a PBL was stored at a lightprotected laboratory (yellow light) with temperature of $19^{\circ}C$ and relative humidity of 57% for 72 hours prior to RM coating (S5), UV curing and spectrometric evaluation. The diffraction efficiency of S5 was reduced by 4.1%, as the alignment started to slightly deteriorate. The remaining three samples were exposed to an unpolarized UV light at a fixed distance and intensity for durations of 30 minutes (S6), 1 hour (S7), and 2 hours (S8). After the experiment, each sample was coated with RM257 and polymerized with UV light and measured similarly for diffraction efficiency. The diffraction efficiency of the S6 and S7 samples decreased by 1.9% and 3.1%, respectively. But after 2 hours, the S8 sample began to appear hazy at the edges and the diffraction efficiency of RN-4942 under different test conditions are negligible and RN-4942, unlike other common photocrosslinking type alignment material specially PVCN, exhibits high thermal, temporal and light exposure stabilities.

In addition, to highlight the significance and advantages of the feasible and efficient fabrication of HOEs with RN-4942, a comparison with the fabrication processes of Brilliant Yellow (BY), a commonly used azo-dye based alignment material, is presented in Table 1.

Photoalignment material	Exposure light	Exposure dosage	Exposure time in our lab	Sensitivity to high-humidity environments	Re-writability after the procedure
BY	488 nm (Blue light)	2-5 J/cm ²	90s	Yes	Yes
RN-4942	355 nm (UV light)	3.5-8.5 mJ/cm ²	2s	Not observed	No

Table 1. Comparisons between Brilliant Yellow and RN-4942 photoalignment material.

Based on the low dosage and noticeably short exposure time requirement of RN-4942, as shown in Table 1, it is evident that RN-4942 is about three orders of magnitude more sensitive to the exposure light used for photoalignment than BY-based alignment layer. This short exposure time ensures that the holography process is inert to time-dependent perturbations of the environment, lowering environmental constraints during HOE fabrication, resulting in excellent alignment quality.

So, in contrast to BY, which is highly sensitive to environmental humidity during fabrication works best in the 20-28% relative humidity [14] and humidity over 40% affects the alignment quality and order parameter of BY alignment layers dramatically [32], the great performance and high efficiency of RN-4942 devices fabricated in 40-45% relative humidity evident that the effect of humidity on RN-4942 is negligible. The hydrophobic groups such as alkyl chains, biphenyl, and phenyl groups in the chemical structure of the liquid crystalline side chain, along with the crosslinking mechanism of RN-4942 photoalignment layer can explain why this material is insensitive to humidity. Moreover, the RN-4942 photoalignment material exhibits no absorption in the visible region and is highly transparent and clear. By considering these critical qualities, RN-4942 has proven to be a strong photoalignment material candidate for use in high throughput processes for mass fabrication of complex liquid crystal holograms.

3. Applications

To emphasize the applications of RN-4942 photoalignment material, beyond merely studying its fabrication, we intend to demonstrate that this planar alignment layer can be used to fabricate various passive monochromatic holographic optical elements, such as PB grating (Fig. 3(a)), PB lens (Fig. 3(b)), PB lens array (Fig. 3(c)), reflective PVG (Fig. 3(d)), and off-axis reflective PVH lens (Fig. 3(e)). In the following subsections, the fabrication process and results for each holographic optical element for green light (λ =532 nm) will be presented.



Fig. 3. Various PBOEs fabricated using RN-4942 photoalignment material: (a) PB grating, (b) PB lens, (c) PB lens array, (d) Reflective PVG, and (e) Off-axis reflective PVH lens.

3.1. PB grating using RN-4942

Conventional refractive optics, such as lens or prism, utilize the optical path difference (OPL) to change the light propagation direction, but the planar LC-based PBOEs, also known as geometric phase, generate the desired phase pattern by spatially varying the LC directors. In this study, a Mach-Zehnder Interferometer (MZI) was used to fabricate the PB grating by polarization holography. As shown in Fig. 4, a linearly polarized (LP) UV laser (355 nm) after passing through the first polarization beam splitter (PBS1), is separated into two orthogonal beams, which are reflected by mirrors and recombined by a second PBS (PBS2) mounted on a mobile X-Y stage, which allows precise control of the interference angle.



Fig. 4. Holographic exposure system for making PB grating.

The beams interfere after passing through a quarter-wave plate (QWP). The interference of these two orthogonal circular polarized (CP) beams will form a rotating orientation of a linearly polarized field on the RN-4942 photoalignment material. Then the photoaligned material is coated with a nematic LC reactive mesogen (RM257) solution. In our experiment, RM257 was first dissolved in toluene with a 1:4 ratio and spin-coated onto the photoaligned RN-4942 sample at 2000rpm and then cured under unpolarized UV light for two minutes to polymerize the RM257

layer. This was followed by a second spin-coating step using RM257 dissolved in toluene at a 1:5 ratio, also spun at 2000rpm, with an additional two-minute curing under UV light. As a result, the RM layer achieved half-wave phase retardation condition for the PB grating at our target wavelength (λ = 532 nm). Figure 5(a) illustrates the director distribution of RM257 aligned to the RN-4942 with a continuously rotating alignment, to act as a PB grating.



Fig. 5. (a) PB grating alignment pattern. (b) $5-\mu$ m pitch PB grating image under a microscope. (c) Measured diffraction efficiency of a 5- μ m pitch PB grating.

The interference between two orthogonally polarized beams, RCP and LCP, generates a field of spatially uniform intensity with a spatially varying polarization state across the plane of interference at the location of the photoalignment sample [33]. The interference angle (θ), which determines the pitch size (Λ) of the grating, is calculated using:

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

In the experiment, our employed laser wavelength is $\lambda = 355$ nm. From Eq. (1), to achieve a grating pitch $\Lambda = 5 \,\mu\text{m}$, the interference angle θ should be set at 2.03°. Figure 5(b) illustrates the 5- μ m pitch PB grating image under the 10x magnification of an Olympus BX51 microscope.

This experiment was done at a laboratory temperature of 22°C and 45% relative humidity before exposure and 17°C laboratory temperature and 51% relative humidity during exposure with UV light, showing that the alignment was not affected by the environment humidity or temperature. The diffraction efficiency of the fabricated PB grating was measured using a UV/VIS/NIR spectrometer to be 99.7% at λ =532 nm (Fig. 5(c)), indicating its high performance and excellent alignment enabled by RN-4942. These PB gratings were fabricated using both RN-4942 solutions with 6 wt.% and 0.5 wt.% concentrations.

To test the performance of the PB grating, first a linearly polarized green laser (532 nm) beam was expanded using a 4f system with focal lengths f1 = 15 mm and f2 = 200 mm, providing a magnification of 13.3. The collimated beam passes through an iris to control the size of the beam before it enters the PB grating, as Fig. 6 shows. A PB grating of half-wave thickness will act as a

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polarizing beam splitter, diffracting the RCP light to the ± 1 st orders and the LCP light to the ∓ 1 st order, depending on the rotation direction of the LC directors. The diffraction angle of each order can be calculated according to the grating equation:

$$\Lambda_x \sin(\theta) = \lambda. \tag{2}$$

In Eq. (2), θ is the diffraction angle, λ is the wavelength of the incident light, and Λ_x is the grating pitch. For $\lambda = 532$ nm and $\Lambda_x = 5 \,\mu$ m, the diffraction angle θ for RCP and LCP beams is 6.1° and -6.1°, respectively. This test demonstrates that the PB grating fabricated with RN-4942 exhibits excellent alignment and performance in green light.



Fig. 6. Experimental setup for testing the PB grating.

3.2. PB lens and mini-lens array using RN-4942

The exposure system for making PB lens and mini-lens array is similar to that of PB grating, with a key difference being the incorporation of a reference phase optical element, such as a lens or a mini-lens array phase profile, in the recording arm of the Mach-Zehnder interferometer (Fig. 7). Both 6 wt.% and 0.5 wt.% RN-4942 solutions can be used in the exposure process.



Fig. 7. Holographic exposure system for making PB lens/mini-lens array.

In this study, the reference phase optical element is a lens with focal length of 100 mm. This setup relays parabolic phase profile of the lens onto the RN-4942 layer. The field should propagate an OPL twice the focal length (200 mm) distance from the lens, if the diameter on the interference plane should match that of the two beams inserted into the MZI. Alternatively, the phase profile imposed onto the field by any optical element may be optically transferred to the interference plane by a 4f optical system, while optionally magnifying or compressing the field to manipulate the referenced phase profile and exposure area. In this setup, the reference phase should be placed at a distance equal to the focal length of the first lens in the 4f system, which is more convenient. Finally, the exposed and post-baked RN-4942 sample is coated with a 1:5 and 1:4 RM257 to toluene solution, each layer spin-coated at 2000rpm and polymerized under

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UV light for two minutes, thereby optimizing the nematic LC thickness to achieve a half-wave condition at green light range.

Figure 8(a) illustrates the radially varying director distribution of the nematic liquid crystal along the parabolic lens pattern of the photoalignment layer and Fig. 8(b) shows a fabricated PB lens with a focal length of 66.7 mm (focal length of the lens times the ratio of the UV laser wavelength to the wavelength it is designed for according small angle approximation) for λ = 532 nm with diffraction efficiency of 99.5% (Fig. 8(c)) under 10x magnification using an Olympus BX51 microscope.



Fig. 8. (a) LC director distribution in a PB lens. (b) Observed PB lens phase profile under an optical microscope. (c) Measured diffraction efficiency of a PB lens.

As mentioned above, PB lens behaves as a half-wave retarder with dual focal points. The sign of the focal point can change depending on the handedness of the incident polarized light. The PB lens exhibits a positive focal length for RCP light and a negative focal length for LCP light. To test the fabricated PB lens with a focal length of 66.7 mm and lens diameter of 20 mm, it is illuminated by the expanded and collimated linearly polarized light of a green laser (532 nm). As Fig. 9 shows, the PB lens behaves like a beam splitter, splitting the linear light of the laser into two orthogonal circularly polarized light beams, while also acting as a lens. 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 lens. These high-performance and highly transparent PB lenses can be employed in a multi-depth system for light field displays.



Fig. 9. Experimental setup to test the PB lens.

High performance of PB lenses indicates exquisite photoalignment of RN-4942. This study was conducted at 22°C laboratory temperature with relative humidity of 21% before and after exposure and 17°C lab temperature with relative humidity 26% during the UV exposure. Unlike sulfuric dye based azo dyes which need a longer exposure for a stable alignment, the exposure dosage was 8.5 mJ/cm² for 2 seconds, ensuring immunity of the fabrication procedure to the mechanical vibrations.

3.3. Short-pitch reflective PVG for AR waveguides using RN-4942

There are two types of polarization volume holograms: transmissive polarization volume holograms (t-PVH) [34,35] and reflective polarization volume holograms (r-PVH) [5]. r-PVH is more suitable for AR waveguides-based near-eye displays due to its wider angular and spectral bandwidth and easier fabrication process [28]. Unlike t-PVH where stray light can pass through, r-PVH reflects it which minimizes the number of ghost images in the system [4]. In general, r-PVH reflects light with the same handedness as the helical structure as the CLC material used in the fabrication, while light with the opposite handedness transmits through the r-PVH.

The large angle interferometer used to fabricate a reflective short-pitch polarization volume gating (PVG) is shown in Fig. 10. In this exposure setup, a linearly polarized UV laser (355 nm) passes through a QWP, which converts the LP light to CP light. The CP light then passes through a PBS, that separates the CP beam into two orthogonal LP beams. The LP beam in each path of the interferometer is reflected by a mirror and directed through an additional QWP and is converted into CP light with opposite handedness. These CP light beams interfere with each other at a specific interference angle. A sinusoidal linear polarization pattern is formed on the RN-4942 alignment layer due to the interference of these two orthogonal CP lights. The interference angle determines the grating pitch of the PVG.



Fig. 10. Holographic exposure system for making PVG.

By using Eq. (1), an interference angle (θ) of 26° and 17.2° was obtained to fabricate a 400-nm and a 600-nm pitch PVG at λ = 532 nm, respectively. The sample was then spin-coated with a CLC solution composed of a 1:2.5 mixture of CLC [2% S5011 (left-handed chiral compound), 3% Irgacure 651, and 95% RM257] to toluene solution. The 6 wt.% RN-4942 solution was used in this experiment. The temperature and relative humidity of the laboratory are 22°*C* and 45%, respectively.

Figure 11(a) illustrates the measured optical efficiency of the 400-nm and 600-nm PVGs. Depending on the application of the PVG, its efficiency can be controlled by the thickness of the CLC layer to satisfy the Bragg condition for a specific wavelength [5]. For example, for maximizing the light coupling into a waveguide, input couplers with very high efficiency are needed. However, for waveguide output-couplers that ensure uniform light extraction, PVGs with relatively low diffraction efficiency are preferred [4,28].



Fig. 11. (a) Measured diffraction efficiency of 600-nm and 400-nm pitch PVGs. (b) Experimental setup to test the PVG.

To test the performance of the fabricated 400-nm short-pitch PVG with a left-handed CLC helical-structure (LH-PVG), a linearly polarized green laser beam (λ =532 nm) that was expanded using a 4f system with f₁ = 15 mm and f₂ = 100 mm, was sent toward the grating. After passing through the left-handed circular polarizer (LH-CP), the obtained collimated LCP light was sent to the LH-PVG which reflects light with the same handedness as the CLC's helical structure, in this case LCP (Fig. 11(b)).

Achieving a significantly short-pitch PVG (400 nm) with high detailed photoalignment quality is an impressive aspect of RN-4942. Such a short-pitch PVG can be used as input and output couplers for AR waveguide combiners to double the optical efficiency and brightness uniformity [28].

3.4. F/0.79 off-axis r-PVH lens for Maxwellian view using RN-4942

According to Fig. 12, the holography exposure system resembles the short-pitch r-PVH gratings. The field of the lens-path of the two-beam interference should propagate an optical path length twice the focal length (2f) distance from the lens, to record the parabolic phase profile which matches the lens. To achieve the grating pitch of 600 nm the interference angle θ = 17.2° is selected for this exposure setup. A lens with a 20-mm focal length is positioned two focal lengths (40 mm) away from the sample in the lens path of the two-beam interference. The RN-4942 sample is irradiated with a 355 nm wavelength UV laser. The temperature and relative humidity of the laboratory during the fabrication was 22°*C* and 45%, subsequently. Afterwards, the sample was overcoated with a CLC solution consisting of a 1:2.5 mixture of CLC (2% R5011, 3% Irgacure 651, and 95% RM257) to Toluene solution.

In this experiment, we used the RN-4942 solution with 6 wt.% concentration. The diameter of the fabricated off-axis lens is 15 mm with a focal length of 11.85 mm. Thus, by using the RN-4942 alignment material, we achieved a fast off-axis lens with the f/# of 0.79 and horizontal half field of view (FOV) of 32.32°, which can be employed for a Maxwellian view combiner.

A Maxwellian view system is a focus-free optical system that uses a lens to converge the collimated light from a display onto the viewers eye lens and then projects the image on the viewers retina (Fig. 13). Therefore, the display image at any depth is always in focus, so this concept can help fix the convergence accommodation problem in near-eye displays. Maxwellian-view systems suffer from a small eyebox, so the off-axis lens must be well-aligned with the user's eye.



Fig. 12. Holographic exposure for off-axis r-PVH lens.

The FOV of this Maxwellian-View near-eye display scales inversely with the f/# of the combiner lens, therefore a small f/# is desirable [30].



Fig. 13. Augmented-reality near-eye Maxwellian-view optical architecture with off-axis combiner lens.



Fig. 14. (a) Measured diffraction efficiency of an off-axis PVH. (b) Experimental demonstration of an off-axis r-PVH lens with f/0.79.

Figure 14(a) shows measured diffraction efficiency of a RN-4942 sample placed in the PVH off-axis lens holography exposure set up. The diffraction efficiency of an off-axis lens is adjustable by controlling the thickness of the CLC layer. Nevertheless, it suffers from fabrication limitations [31]. Additionally, Fig. 14(b) depicts the experimental setup for testing the fabricated off-axis r-PVH lens. An expanded and collimated RCP, after passing through the iris and right-hand circular polarizer (RH-CP), green laser beam was used to illuminate the device at an off-axis angle of approximately 32.3° The outgoing beam is deflected normally to the r-PVH lens and focused at 11.85 mm, as the red arrow indicates.

In summary, using RN-4942 photoalignment material for the fabrication of various high-quality LC holographic devices proves that it is a strong candidate for the reliable and scalable production of transmissive PBOE and reflective PVH optical devices.

4. Conclusion

We investigated the properties, fabrication procedure and applications of RN-4942 as liquid crystal photoalignment material. In comparison with photocrosslinking alignment material, RN-4942 offers resistance to high temperatures up to $100^{\circ}C$, temporal stability for 72 hours and photostability under unpolarized UV light up to 2 hour. Additionally compared to azo-dyes based alignment layers such as BY and SD-1, RN-4942 demonstrates ~1000x higher sensitivity to photoalignment exposure light, and by consequence allows a faster exposure time (in this experiment 2 seconds). We have also observed a greater resistance to environmental disturbances such as changes in temperature (from $22^{\circ}C$ to $17^{\circ}C$ and vice versa), relative humidity (20-45%), and mechanical misalignment. These properties ensure a highly reliable, stable and efficient fabrication process with precise and long-term alignment stability.

Additionally, we successfully fabricated various high-quality and high-performance passive HOEs including PB gratings and PB lenses with approximately 99% diffraction efficiency, as well as 400-nm and 600-nm reflective PVGs that suitable for input and output couplers of waveguide combiners. Furthermore, we fabricated an ultra-fast PVH lens with an f/0.79 ideal for Maxwellian view systems.

Overall, RN-4942 offers a simple and stable fabrication process while enabling high-quality optical elements, making it an exceptional potential choice for mass industrial fabrication of advanced planar optical components elements, which are commonly used in AR/VR optical architectures.

Acknowledgments. The authors are indebted to Nissan Chemicals for providing the RN-4942 samples for testing and the measured absorption spectrum.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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