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Stretchable, flexible, and adherable polarization volume grating film for waveguide-based augmented reality displays

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Abstract

We report a stretchable, flexible, and adherable polarization volume grating (PVG) film and propose a compact optical system for augmented reality displays based on it. The Bragg reflection band shift, deflection angle change, and the mechanical robustness under stretch-release cycles of the PVG film are also investigated.

KEYWORDS

augmented reality, liquid crystals, near-eye display system, polarization volume grating, stretchable film

1 | INTRODUCTION

Augmented reality (AR) display devices, such as Google Glass, Microsoft HoloLens, and Magic Leap One, have found many practical applications. However, these see-through near-eye displays are still facing several technical challenges, such as higher optical efficiency, wider field of view, lighter weight, and smaller size in order to accelerate widespread applications.

Recent progresses in liquid-crystal polarization volume grating (PVG) provide more possibility in waveguide-based AR displays.[1–5] Compared with conventional volume gratings used in AR devices, such as holographic volume gratings, PVGs can achieve nearly 100% first-order efficiency at a very large diffraction angle, and moreover, they only respond to certain circularly polarized light. Besides these distinctive optical features, the elasticity of liquid crystal (LC) polymers[6–9] not only grants stretchability and flexibility[10] but also enables tunable periodicity for the diffractive optical elements. The latter characteristics allow the precise control of diffraction angle and Bragg wavelength.

In this paper, we demonstrate a reflective PVG film based on LC polymer. Such a stretchable PVG film possesses promising advantages and potentials for AR displays, laser beam steering, and optical communication systems.

2 | DEVICE FABRICATION

The brilliant yellow (0.4 wt%) dissolved in dimethylformamide (DMF)[11] was spin coated onto a clean glass substrate at 800 rpm for 5 seconds and then 3000 rpm for 30 seconds as photo-alignment layer. The substrate was then exposed on two-beam interferometer ($\lambda = 457$ nm) with one beam being left-handed circularly polarized (LCP) and the other being right-handed circularly polarized (RCP). The angle between two beams was set at 40°. The PVG precursor consisting of 2.4 wt% chiral agent R5011 (HCCH, helical twisting power Helical Twisting Power [HTP] ≈ 108/μm), 5 wt% initiator Irgacure 651, and 92.6 wt% photo-curable monomer RM257 (HCCH) was diluted in toluene. The precursor was spin coated onto the exposed substrates then cured with UV light in nitrogen environment. A thin film of PVG was formed on glass substrate. Polydimethylsiloxane (PDMS) was prepared by mixing Sylgard 184 Silicone Elastomer with the curing agent at 10:1 ratio[8] followed by 30 minutes of degassing in vacuum chamber. The prepared PDMS precursor was spin coated onto the PVG and cured for 4 minutes at 110°C to create smooth and uniform film. Because of the comparatively high affinity of PVG to PDMS, both films can be detached from the glass substrate, and a flexible PVG on PDMS was obtained.

As Figure 1 illustrates, in the regions exposed by interferometer, the LC directors self-organize into PVGs (purple region). For the unexposed area (green region), no in-plane periodicity was defined, and thus, uniform symmetric helix was formed, like a regular cholesteric texture.[12,13]

Figures 2A, 2B, and 2C show the light deflection, rollability, and flexibility, respectively, of a 3-μm-thick PVG fabricated on a 160-μm-thick PDMS substrate. At this specific angle (Figure 2A), the diffracted light from PVG appeared green. Then, we rolled the sample to a radius of curvature of 3.3 mm, as Figure 2B shows. No change in performance was observed, showing good rollability of the flexible PVG structure.

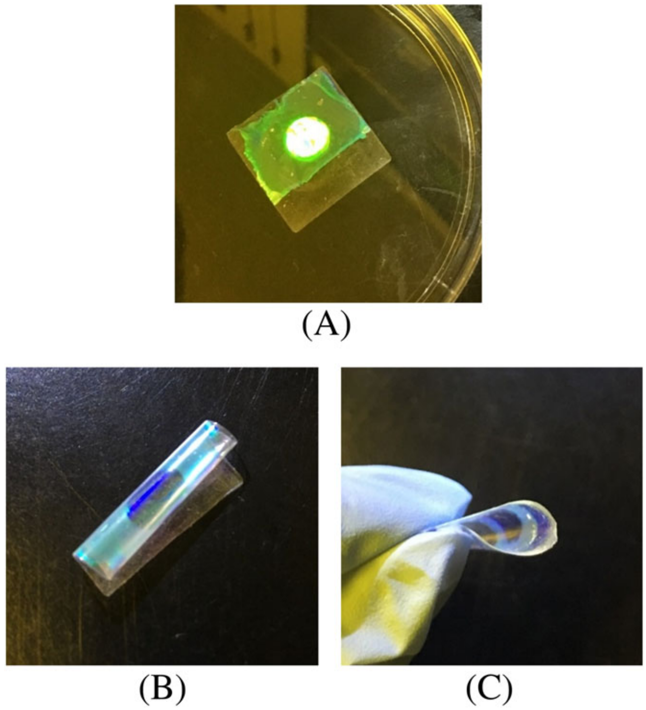

FIGURE 2 Images of a 3-μm thick polarization volume grating (PVG) on a 160-μm thick PDMS substrate. A, Green diffraction of PVG is observed in the central area where interference exposure occurred. B, Rolled sample with a radius of curvature of 3 mm. C, Folded sample

3 | RESULTS AND DISCUSSIONS

Firstly, we observed the change in horizontal periodicity Λ_x under microscope as Figure 3 depicts. The initial length of PVG was 6 mm, and we increased the stretch length along horizontal direction from 0 (initial state) to 2.4 mm. The stretching length from Figure 3A to 3B was 0 to 2.4 mm. During stretching, we found the periodicity gradually changed from 667 to 775 nm, confirming that lateral stretch causing the increased horizontal period of PVGs.

We measured the first-order diffraction efficiency and central wavelength shifting with respect to the applied strain. Results are plotted in Figure 4. As the stretch length increases, the horizontal periodicity gradually increases, and the film thickness decreases, resulting in a blue shift of the reflection band and slightly decreased diffraction efficiency (from 95.1% to 92.7%). Here, we recorded 5 points during the strain for spectral analysis. When the stretch length exceeds 2.44 mm, the PVG film approaches its elastic limit. Further stretch would lead to visible cracking of the PVG film.

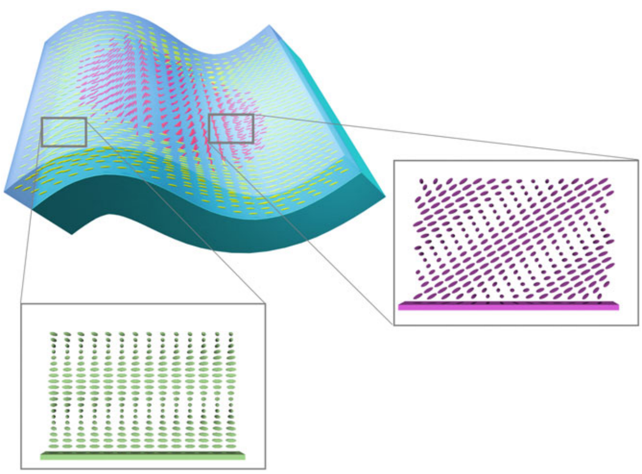

FIGURE 1 Schematic illustrations of polarization volume grating (PVG) structure

The deflection angle of PVG is directly determined by its horizontal periodicity Λ_x, and therefore, it is subject to change under strain. The measurement setup is shown in Figure 5A. A 532-nm laser diode was used to characterize the change in diffraction angle at normal incidence. Upon diffraction, the beam spot was projected onto a screen, which was set parallel to the probe laser. From trigonometry, the first-order diffraction angle was calculated for different applied strains, as plotted in Figure 5B. The diffraction angle decreases at higher strain as expected. As the stretch length increases from 0 (unstrained) to 2.44 mm (40.6% strain), the angle changes from 35° to 46.5°, setting the tuning range of 11.5°. Such a continuous control of diffraction angle has potential for laser beam steering applications.

To test the mechanical robustness of the stretchable film, we replace the manual translational stage with a precision motorized translational stage (ESP300, Newport) as shown in Figure 6.

Before stretching, the film was measured at a periodicity of 667 nm, and then, we increased the strain to 33.3% (2 mm stretch length) and released the film and then repeated this stretch-release cycle. We measured the periodicity after each 10 cycles. We observed and recorded a

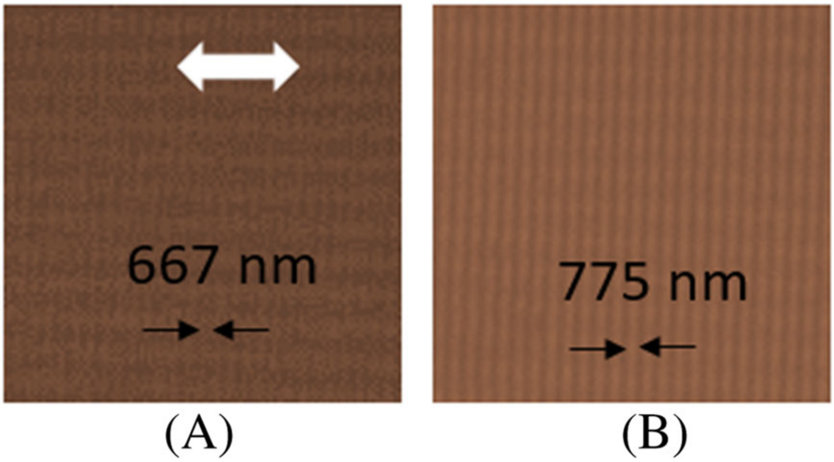

FIGURE 3 Optical microscope images of polarization volume grating (PVG) fabricated on PDMS under different strain. The size of each picture is 20 μm × 20 μm, and stretching was along the arrow labeled in A. The periodicity was measured to be A, $\Lambda_x \cong 667$ nm and B, $\Lambda_x \cong 775$ nm

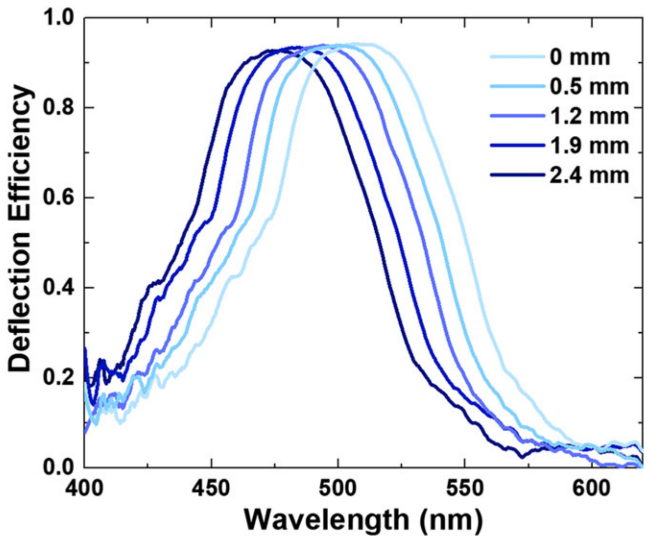

FIGURE 4 Measured stretch-induced first-order diffraction spectra and efficiency. Curves from right to left correspond to the stretched length as indicated

change in periodicity at 0% strain from 667 to 740 nm, and yet the PVG on PDMS did not show any crack or wrinkle. This suggests that the PDMS film underwent permanent deformation after 20 cycles, but PVG was still within its elastic limit. Further stretching cycles did not change the periodicity at 0%.

If the pattern of PVG is damaged, the diffraction beam is not able to keep the spot shape. Moreover, both scattering and haze will appear. Since the ductility of PDMS is much higher than that of PVG itself, crack or wrinkle will occur when PVG itself exceeds the elastic limit. By contrast, the PDMS remains smooth even it cannot be full recovered. Therefore, a prestrain treatment or a modification in formulation of PDMS was required for better mechanical robustness.

4 | APPLICATIONS FOR AR DISPLAYS

4.1 | Waveguide coupler in AR system

This high efficiency, large deflection angle, thin PVG film has promising application in AR displays. Due to the adhesion of PDMS substrate, the film can be easily laminated onto a smooth surface, such as a glass slab. Figure 7A illustrates a possible application of the PVG film in a see-through near-eye system.

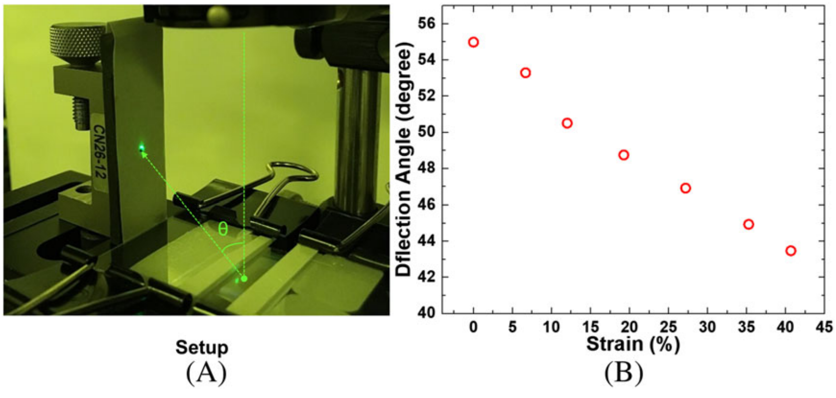

FIGURE 5 A, Image of experimental setup. The diffraction angle (θ) was marked with green dashed lines. B, Measured diffraction angle at λ = 532 nm under different stretched length, starting from the initial state

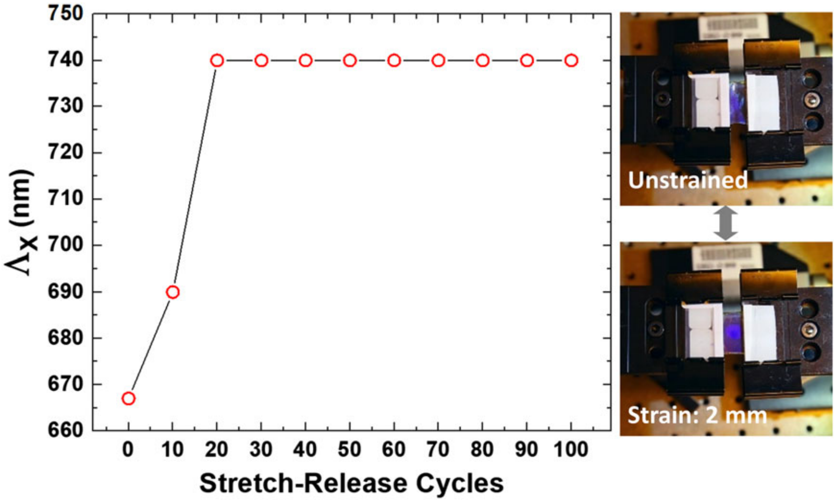

FIGURE 6 Measured horizontal periodicity of polarization volume grating (PVG) as a function of stretch-release cycles, starting from the initial state. Right: the film was fixed on the electrical holding stages at completely unstrained state. The stretch length was defined by the increased distance between the clamps. Then repeat the stretch-release cycles form unstrained state to 2 mm

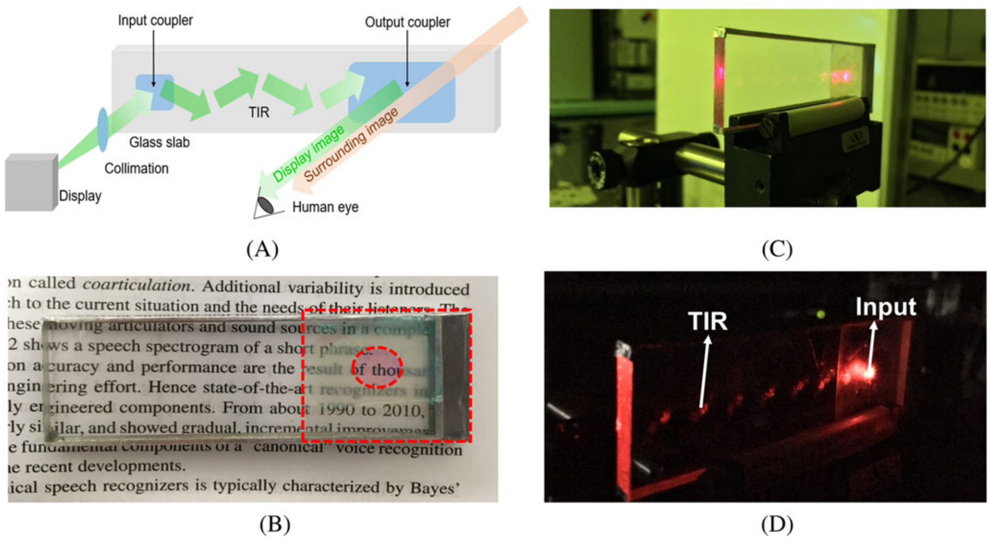

FIGURE 7 A, Polarization volume grating (PVG) films used as waveguide couplers in augmented reality (AR) see-through near-eye system. B, The image of glass slab attached with PVG film. C, The PVG film is adhered on a glass slab. The wavelength of light source is 632 nm. D, The red light is coupled into the waveguide, we can clearly see the input spot and the TIR

To demonstrate feasibility, we attached our PVG film on a glass slab as depicted in Figure 7B. The red rectangular dashed lines show the film region, and the PVG is circled in the center. The PVG region is reddish and clear, by contrast, the unexposed area is greenish with some scattering. Then, we measured the scattering of the circled PVG using an integrating sphere. The scattering of PVG is lower than 5%. Since PVG itself is clear, the scattering mainly originates from the tiny bubbles in PDMS. A 632-nm laser diode was used to test whether the light can be coupled into the waveguide by the PVG film. The experimental result is also included in Figure 7. We can see the input light spot on the PVG film and the leaked light at the edge in Figure 7C. To observe the input spot and the total internal reflection (TIR) clearly, we dim the ceiling light, and the image is shown in Figure 7D. Here, we use a red-color diode laser to demonstrate the potential application. For AR see-through system, the image quality is not only dependent on the performance of the coupler but also highly related to the image source and system design.

4.2 | New AR system based on PVG film

Furthermore, the film can also be adhered on a curved surface as long as the curvature is not too large. The combination of a convex lens and a PVG film is equal to a reflective off-axis lens. Figure 8A shows the image of such a combination. To compare the difference between the original convex lens and the reflective off-axis lens, we

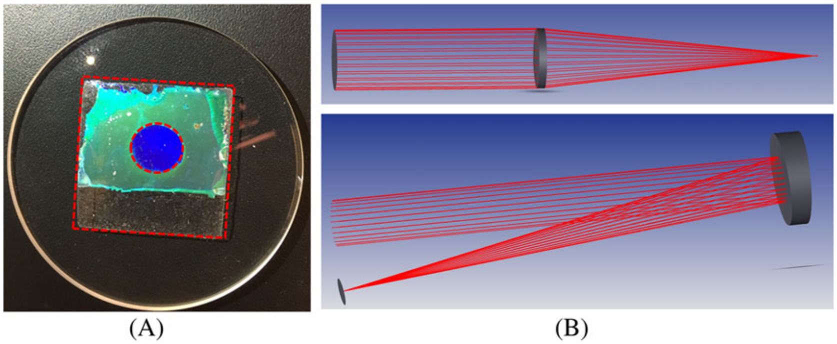

FIGURE 8 The rendered images for A, subframe 1 and B, subframe 2. The fast switching of these two subframes results in an additive-intensity light field, which resembles the designated 3D scene

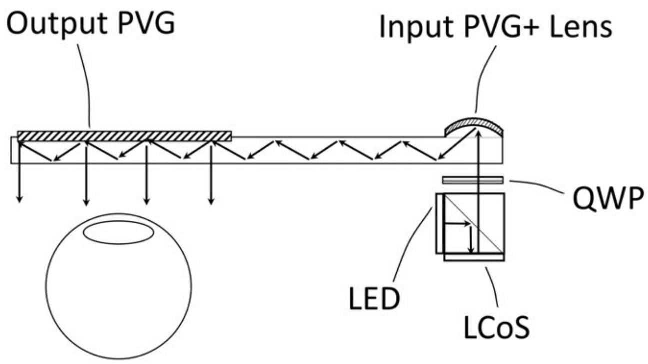

FIGURE 9 The optical design based on polarization volume grating (PVG) film

use ZEMAX to simulate the device structure, and the schematic diagram is shown in Figure 8B.

On the basis of the PVG film described above, we propose a more compact AR optical design as illustrated in Figure 9.[14] The light source generates a uniform output, which is reflected by a polarizing beam splitter (PBS) toward a liquid crystal on silicon (LCoS) panel.[15] The displayed content is then reflected toward a quarter-wave plate (QWP) to convert the linearly polarized light into circularly polarized light. The light is then passed through waveguide and collimation lens. Upon reflection by the combination of convex lens and PVG film, the light is collimated and then deflected into the waveguide. The second PVG film in the output is disposed to deflect again and guided light into the viewing region. In this design, the waveguide, collimation lens, and the input coupler are integrated to achieve a compact structure.

5 | CONCLUSION

We have experimentally demonstrated a stretchable, flexible, and adherable PVG film based on PDMS substrate with tunable periodicity and high diffraction efficiency. The PVG film has reasonable robustness and can be further improved by chemical engineering. Besides, the PVG film provides a new solution for a more compact AR optical system design. We believe this work will make good impact to the AR displays.

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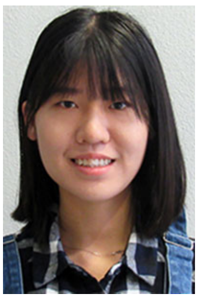

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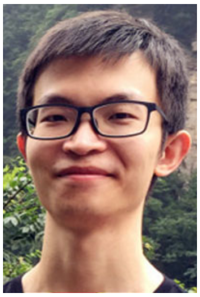

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