Photo-patterned Cholesteric Liquid Crystals for Transparent Computer-generated Waveguide Holography with Visible Playback Capability

SeongYong Cho, Hiroyuki Yoshida, Masanori Ozaki

Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, 2-1 Yamada-oka, Suita, Osaka, 565-0871, Japan

Keywords: Cholesteric liquid crystal, Holography optical element, Waveguide holography

ABSTRACT

A completely transparent waveguide holography in the visible light region is demonstrated based on a photo-patterned cholesteric liquid crystal, which reflects only infrared light. The transparent device also demonstrates that the encoded optical phase information can be coupled out of waveguide mode through visible wave-guided light and observed in free-space.

1 INTRODUCTION

Holographic optical elements (HOEs) enable to reconstruct arbitrary wavefronts, which find a number of applications such as security elements, data storage, and displays. There is recently an increasing attention in HOEs as they can be used to light coupling elements of waveguide-type see-through displays, which is one of the promising technology for next-generation displays. Conventional HOEs are fabricated by recording the interference pattern of two light beams on photo-reactive materials, but they are only partially transparent (wavelength or polarization dependence) due to the appearance of Bragg reflection band in the visible light region [1]. HOEs that can simultaneously implement transparency and high reflectivity are an important development, which potentially improve the brightness performance of see-through-type displays.

Liquid crystal (LC) materials are attractive materials as they enable to realize HOEs based on the Phancharatnam-Berry (PB) phase. When circularly polarized (CP) light is incident on a nematic LC device with half-wave retardation, the polarization of transmitted light is converted to opposite CP light with additional phase shift twice with respect to the optical axis of the LC molecules. [2]. Thus, various transmissive HOEs such as gratings [3], lenses [4], and holograms [4] can be realized by appropriately designing the distribution of the optical axis of LC molecules on a substrate.

On the other hand, cholesteric liquid crystals (ChLCs), which have been long known as self-organizing mirror-like reflectors, can be also employed to implement reflective HOEs [5, 6]. When the geometric phase of the helix is controlled from 0 to π radian on a substrate, the phase of Bragg reflected light can be modulated from 0 to 2π radians [5, 6]. Thus, by appropriately designing the helical phase distribution of ChLCs on a substrate, various reflective HOEs such as deflectors [5], lenses [5], and holograms [6] have been be realized. Here, we present a computer-generated waveguide hologram (CGWH), which is completely transparent in the visible light region, based a photo-patterned ChLC. We first show a fact that all higher-order reflections of ChLCs are negligible in the visible light region to implement transparent HOEs.

2 NUMERICAL SIMULATION OF BRAGG REFLECTION BAND OF CHLCS.

ChLCs have a sinusoidal modulation of the dielectric tensor distribution and exhibit a Bragg reflection over a wavelength band given by $n_o p$-$n_e p$, where n_o and n_e are the ordinary and extraordinary refractive indices and p is the helical pitch. Because it possesses only a single Fourier component, all higher-order reflections are suppressed for normal incidence and negligible for oblique incidence. We support this fact by numerically calculating the Bragg reflection band of a ChLC through Berreman's 4 × 4 method [7]. A left-handed ChLC with the numerical parameters of n_o = 1.53, n_e = 1.75, and p = 600 nm was assumed to be sandwiched between two glass substrates (n_g = 1.53, n_g is the refractive index of the glass substrates) with a gap of 9 μm.

Figure 1 shows the simulated Bragg reflection band depending on the incident angle when illuminated by left- and right-circularly polarized light (L and RCP). Indeed, we confirm that the higher-order reflections are suppressed for normal incidence in both CP light. The higher-order reflections appear at the angled incidence, but they are insignificant (>10%) when considered that the incident light on the ChLC device is refracted at the interface between the glass substrate and the air, limiting the maximum angle of incidence up to 41º (white dashed line in Fig. 1). Thus, a transparent optical device can be implemented by appropriately designing the Bragg reflection band of the ChLC in infrared region. This is a unique optical characteristic, which is not observed in

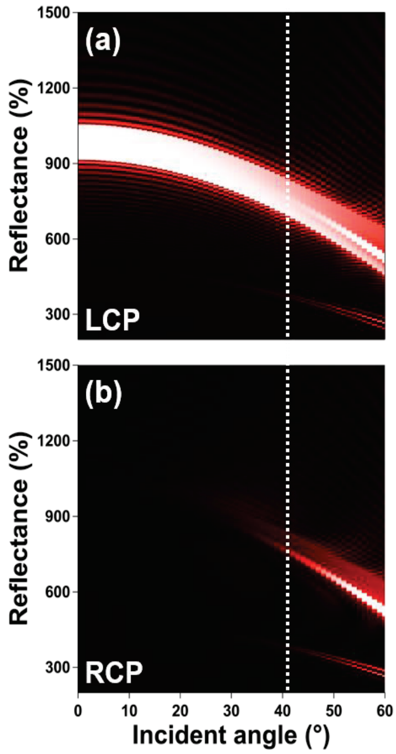

Fig 1. Simulated angular dependence of Bragg reflection spectrum of the ChLC upon LCP (a) and RCP (b) illumination. The white dashed line indicates the maximum angle of incidence when the device is placed in air.

similar periodic structures such as standard dielectric multilayer because they show strong higher-order reflections in the visible light region.

3 COMPLETELY TRANSPARENT CGWH

3.1 Fabrication and design of the CGWH

Figure 2 (a) schematically shows the design of the CGWH, which the ChLC-based HOE was attached at the end of the waveguide layer that has the refractive index and the thickness as 1.53 and 0.7 mm, respectively. The incident light was coupled with the waveguide layer through a coupling prism. The propagation angle was designed sufficiently large so that the visible wave-guided light to be reflected by ChLC-based HOEs. The reflected light was decoupled out of the waveguide mode, and projected on a screen 30 cm away from the CGWH device after passing a projection lens.

To fabricate the CGWH, we prepared two glass substrates with sizes of 5 × 2 cm^2 (for waveguide layer, d = 0.7 mm) and 2 × 1.5 cm^2. A photo-alignment agent (LIA-03, DIC) was coated on both substrates, and the smaller substrate was then attached at the end of the large one with a gap of 9 μm.

To decouple out of the hologram from waveguide mode, an off-axis source image (Osaka university logo) was prepared as shown in Fig. 2 (b). The center of the Osaka

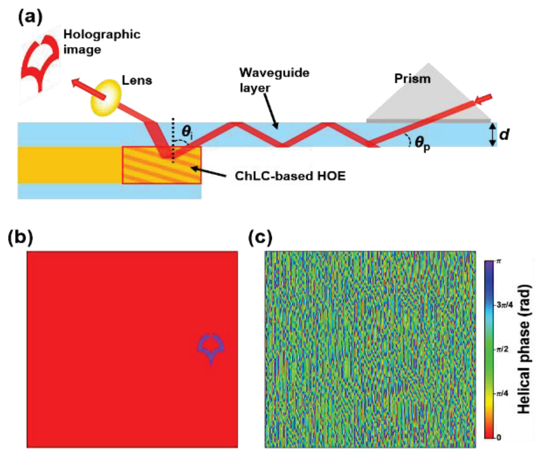

Fig. 2. Design of the CGWH. (a) Schematic of the waveguide device. d: thickness of the waveguide layer. θ_p: propagation angle of wave-guided light. θ_i: incident angle on the ChLC-based HOE. (b) Target image of the hologram. (c) Retrieved helical phase distribution corresponding to the source

university logo is placed 190 pixels away from the center of the image plane to make the holographic image to be deflected by following equation [8]:

$$\tan\theta_d = \frac{N_a \lambda}{n N_x \Delta a}, \qquad (1)$$

where θ_d is the deflection angle, N_a is the number of pixels from the center of the image plane to the center of the Osaka university logo, λ is the wavelength of light, n is the refractive index of waveguid medium, N_x is the total number of horizontal pixels, and Δa is the horizontal pixel size. The optical phase distribution was retrieved through the Gerchberg-Saxton (G-S) algorithm [9], which reconstructs a 2D holographic image when illuminated by light with wavelength falling in the Bragg reflection band. The helical phase information shown in Fig. 2 (c) was obtained by multiplying a factor of 0.5 at the optical phase information retrieved through G-S algorithm.

The helical phase information was imparted in the device by a maskless photo-patterning method [5]. The patterning process consist of 512 × 384 pixels with a pixel size of 0.66 × 0.66 μm^2, which provide the size of a photo-patterned area of ~ 0.34 × 0.25 mm^2. The pattern was conducted with 12 × 10 arrays, which gives a size of the total device area of ~ 4 × 2.5 mm^2. The phase step for the patterning process was 10° (18 phase levels).

After the patterning process, a ChLC, which was prepared by mixing a nematic LC mixture (MLC-2140, Merck) and a chiral dopant (S-5011, HCCH) at a weight concentration of 98.7:1.3, was injected in the photo-patterned device at 100°C and cooled down to room temperature.

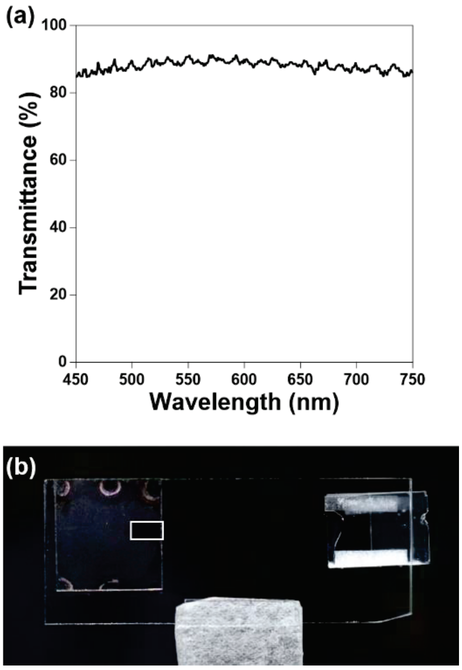

Fig. 3. Fabricated CGWH. (a) Measured transmission spectrum of the photo-patterned ChLC in the visible light region. (b) Photograph of the fabricated CGWH. The area surrounded by the white square indicates the photo-patterned ChLC.

3.2 Result and discussion

Figure 3 (a) shows the transmission spectrum of the ChLC-based HOE, which demonstrate that no higher-order reflections are observed and an average transmittance over 88% is achieved in the visible light region. Figure 3 (b) is a photograph of the fabricated CGWH, which supports the fact that the photo-patterned area is completely transparent under ambient lighting.

Because of the limitation in the angle of light incidence on the device, the device is rendered transparent under ambient lighting; however, using the fact that the reflection band of ChLCs blue-shifts upon angled incidence, it is possible to design a device such that visible light that is guided through the waveguide layer is reflected by the ChLC-based HOEs and reconstructs the holographic image. In the design, the propagation angle of wave-guided light was set as 40° [θ_p in Fig. 2 (a)], which makes the light to be incident on the ChLC-based HOEs as an angle of 50° [θ_i in Fig. 2 (a)] with respect to the boundary normal of the CGWH device. Figure 4 (a) shows the reflection spectrum of the ChLC at an incident angle of 50 ° , showing that the total reflection band appears approximately 650 nm (in red region) with a bandwidth of 20 nm. This result is in good agreement with the calculation results in Fig. 1.

Figure 4 (b) and (c) shows the holographic images,

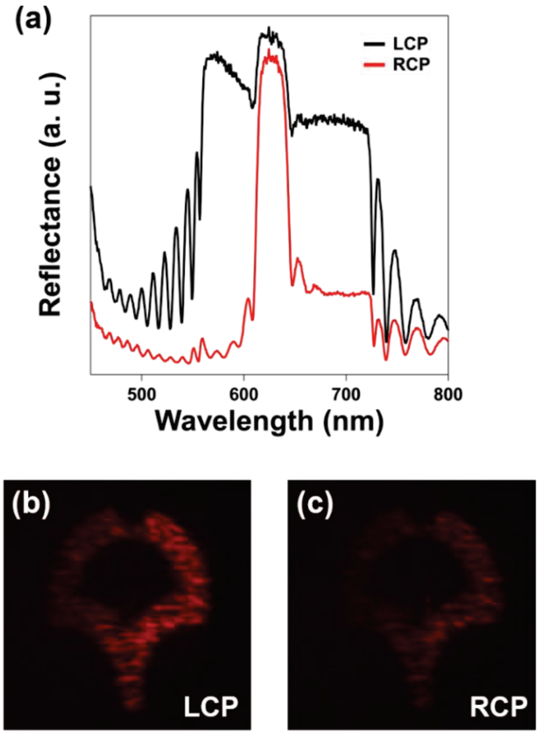

Fig. 4. Playback of the hologram. (a) Bragg reflection band of the ChLC at the incident angle of 50º. (b,c) Decoupled holographic image upon LCP (b) and RCP (c)

which are played back from the transparent CGWH, using red visible light (λ ~ 650 nm) that is illuminated on the sample through the substrate as a waveguide mode. In Eq. 1, based on the values used in the experiment where N_a is 190 pixels, λ is 650 nm, n is 1.53, N_x is 512 pixels, and Δa is 0.66 μm, the deflection angle of the played back holographic image is evaluated as an angle of 13.4°. It makes the wave-guided light to no longer satisfy the angle of total internal reflection, resulting in out-coupling of the holographic image. As expected, the holographic image is clearly decoupled out of the waveguide mode and visible in free-space on a screen placed at a distance of ~ 30 cm from the CGWH device. This result shows the feasibility of our work for light coupling elements of waveguide-type see-through devices.

4 CONCLUSION

In conclusion, we have demonstrated a completely transparent CGWH in the visible light region based on a photo-patterned ChLC. We have realized the transparent ChLC-based HOE by using the fact that all higher-order reflections of the ChLC are insignificant under ambient lighting. In addition, the encoded hologram can be played back by wave-guided visible light and decoupled out of the waveguide mode, enabling to clearly observe in free-space. The concept proposed here offers new opportunities for light coupling devices, where simultaneous achievement of transparency and high reflectivity is required such as see-through displays. In addition, we expect that large-area devices can be realized by coating photo-curable LC materials on a pre-treated substrate through spin-coating or roll-to-roll method.

ACKNOWLEDGMENTS

The authors thank DIC Corporation and JSR Corporation for providing alignment materials. This work was supported by JSPS KAKENHI (17H02766), JST PRESTO (JPMJPR151D), and Osaka University Innovation Bridge Grant.

REFERENCE

[1] Yu, C., Peng, Y., Zhao, Q., Li, H. & Liu, X. Appl. Opt. 56, 9390-9397 (2017).
[2] Marrucci, L., Manzo, C. & Paparo, D. Appl. Phys. Lett. 88. 221102 (2006).
[3] Honma, M. & Nose, T. Appl. Opt. 43, 5193-5197 (2004).
[4] Serak, S. V. et al. J. Opt. Soc. Am. B 34, B56–B63 (2017).
[5] Kobashi, J., Yoshida, H. & Ozaki, M. Nat. Photon. 10, 389-392 (2016).
[6] Kobashi, J., Yoshida, H. & Ozaki, M. Sci. Rep. 7(1), 16470 (2017).
[7] Berreman, D. W. *J. Opt. Soc. Am.* **62**, 502-510 (1972).
[8] Goodman, J. W. Introduction to Fourier Optics (McGraw-Hill, 1996).
[9] Gerchberg, R. W. & Saxton, W. O. Optik 35, 237-246 (1972).