Electrically switchable computer-generated hologram recorded in polymer-dispersed liquid crystals

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A computer-generated hologram (CGH) designed using the iterative Fourier transform algorithm was recorded in a cell filled with a polymer-dispersed liquid crystal material under a collimated He–Ne laser beam operating at 543 nm. Due to the photopolymerization induced phase separation, an index modulation was formed between the polymer-rich and liquid-crystal-rich regions. The results showed a good reconstructed image. With a suitable voltage applied, the reconstructed image can be erased due to the index change between the polymer and liquid crystal. Such electrically switchable CGH is potentially useful in information storage and adaptive optical elements. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2736270]

Computer-generated hologram (CGH) is widely known as a useful tool for wave front manipulations[1] and optical information processing.[2–6] It enables the creation of very sophisticated optics without any limits as to what the final diffraction pattern may look like. Many kinds of materials have been used to record CGHs. Previously, CGHs have been recorded in photorefractive materials such as Fe doped $LiNbO_3$ single crystal[7] and $BaTiO_3$ crystal.[8] Guessous *et al.* even used the bacteriorhodopsin as the recording material for CGH.[9] In some adaptive applications, electrically tunable holograms or diffractive elements are highly desirable due to easy control and real-time operation. Although real-time CGH can be realized based on liquid crystal (LC) spatial light modulators (SLMs),[10,11] the response time is generally slow ($\geqslant$10 ms). By adding a portion of polymer, the response time which is dependent on the polymer concentration can be improved.

Polymer-dispersed liquid crystal (PDLC) material has been extensively investigated for electro-optical applications.[12–15] A vitally important method used to construct PDLC devices is photo-polymerization induced phase separation (PIPS) by either uv or visible lasers, depending on the materials used. The unique property of polymer/LC composite devices is that they can be electrically tuned or switched, which is useful for adaptive optical devices. PDLC also shows a potential for high capacity data storage. Optical image storage in PDLC was reported using a conventional holography technique.[16–18] In this letter, we shall report an electrically switchable CGH recorded in a PDLC cell with an improved response time compared to conventional LC SLM.

In our experiment, the materials used to record CGH were monomer, trimethylolpropane triacrylate (TMPTA); cross-linking monomer, *N*-vinylpyrrolidinone (NVP); surfactant, octanoic acid (OA); coinitiator, *N*-phenylglycine (NPG); and photoinitiator, rose bengal (RB); all from Aldrich. In prepolymer, the ratio of TMPTA/NVP/OA/NPG/RB was 62/25/10/2/1 by weight.[19] In prepolymer/LC mixture, the LC concentration was about 35 wt %. The LC used was E7 (Merck) with an ordinary refractive index of $n_o=1.521$ and a birefringence of $\Delta n=0.225$. The detail material preparation processes can be found elsewhere.[15] The mixture was injected into a LC cell by capillary action at room temperature. The cell gap was 8 μm.

The phase distribution of the CGH was designed using the conventional iterative Fourier transform algorithm.[20] We encoded the letters "NTU" [Fig. 1(a)] into the CGH, consisting of 128×128 binary-phase-only pixels. The phase value of each pixel is either 0 or π. Then the CGH was transferred to a transparency mask with an effective area of 6.4×6.4 mm^2 and a resolution of 50 μm. The phase distribution of the CGH on the mask is shown in Fig. 1(b), where the black and white regions represent phase values of 0 and π, respectively. The reconstructed image of the CGH simulated is shown in Fig. 1(c). Due to the binary phase-only structures, we can see the reconstructed twin images corresponding to the $\pm$1st orders. Then the CGH photomask was clipped onto the LC cell filled with prepolymer/LC mixture, and subjected to a collimated He–Ne laser (543 nm) beam for recording the phase distribution by PIPS. It is worth mentioning that the laser has only about 4 mW output power. The intensity impinged on the sample after collimation is only around 0.5 mW/cm^2. The optimized exposure time was 10 min in our experiment judged from the fading of the RB color.

Figures 2(a)–2(c) show the typical morphologies under a microscope for three representative microregions after phase separation. It can be seen that a good separation between the polymer and LC happened inside the cell, where the darker and brighter areas were polymer-rich and LC-rich regions, respectively. In our configuration, the refractive index of the polymer, n_p, is set to be equal to the ordinary refractive index of the LC, n_o. Without voltage applied, the LC molecules are randomly distributed, and an effective refractive index larger than that of the polymer is present in the bright regions. As a result, there is an index difference between the LC-rich and polymer-rich regions. Upon applied voltage, the LC director will align along the direction of the electric field. If the indices of LC and polymer are matched, the composite film becomes a homogeneous medium and thus the phase difference disappears.

The relative phase difference ($\Delta\delta$) between the adjacent LC-rich and polymer-rich regions can be written as $\Delta\delta=2\pi(n_{\text{eff}}-n_p)d/\lambda$, where d is the cell gap, λ is the wave-

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FIG. 1. Encoded the letters "NTU" (a), phase distributions of the CGH on the transparency (b), and reconstructed image of the CGH simulated (c).

length, and n_{eff} and n_p are the LC effective refractive index and polymer refractive index, respectively. The polymer-rich regions can be considered to contain pure polymer without any LC, while the LC-rich regions are filled with polymer and LC (only 35 wt % of LC in the initial mixture). From the optical microscopic images in Fig. 2, the area ratio (also the volume ratio) of polymer-rich region is statistically estimated to be 16% with a standard deviation of 1.53%. Assuming the volume ratio of polymer is the same as the corresponding weight ratio (65 wt %), with a 5% volume shrinkage for polymer during polymerization, there is about 44% polymer distributed in the LC-rich region. As a result, the LC-rich regions consist of 56% polymer and 44% LC. The effective index of the LC-rich region can then be calculated by $n_{\text{eff}} = fn_p + (1-f)n_{\text{LC}}$, where f is the volume fraction of the polymer in the LC-rich region. In our experiment, $n_p = 1.522$,[14] $n_{\text{LC}} = (2n_o + n_e)/3 = 1.596$, the estimated effective index of the LC-rich region is around 1.554 with a standard deviation of 7×10^{-4}. Thus, the relative phase difference estimated is around 0.9π, which is close to the desired phase difference of π.

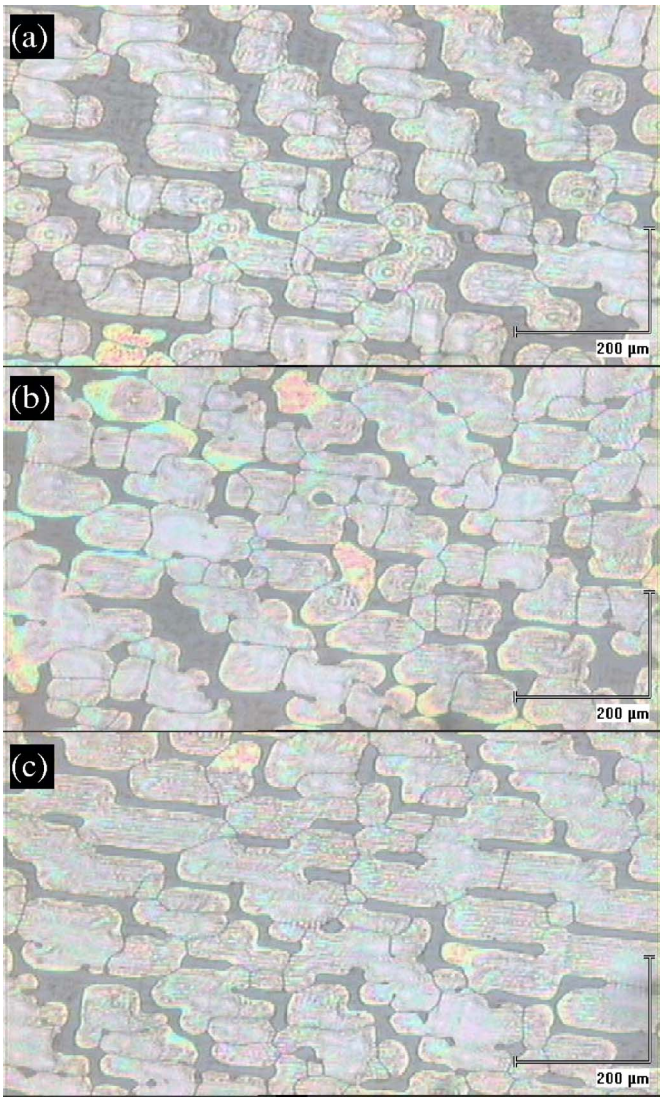

FIG. 2. (Color online) Typical optical microscopic images [(a)–(c)] at three microregions of the PDLC with CGH recorded.

Figure 3 shows the optical setup for image reconstruction from the hologram. Light from a green He–Ne laser is firstly incident on a spatial filter system consisting of an objective lens and a pinhole. The expanded beam is then collimated and falls on the LC cell. A Fourier transform lens is used to produce the Fraunhofer diffraction pattern of the hologram in its focal plane. Because the image is too small to observe, a second objective lens with 20× magnifications is used to magnify the image.

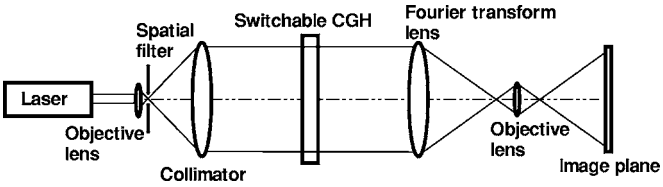

FIG. 3. Optical setup to reconstruct the image from PDLC CGH.

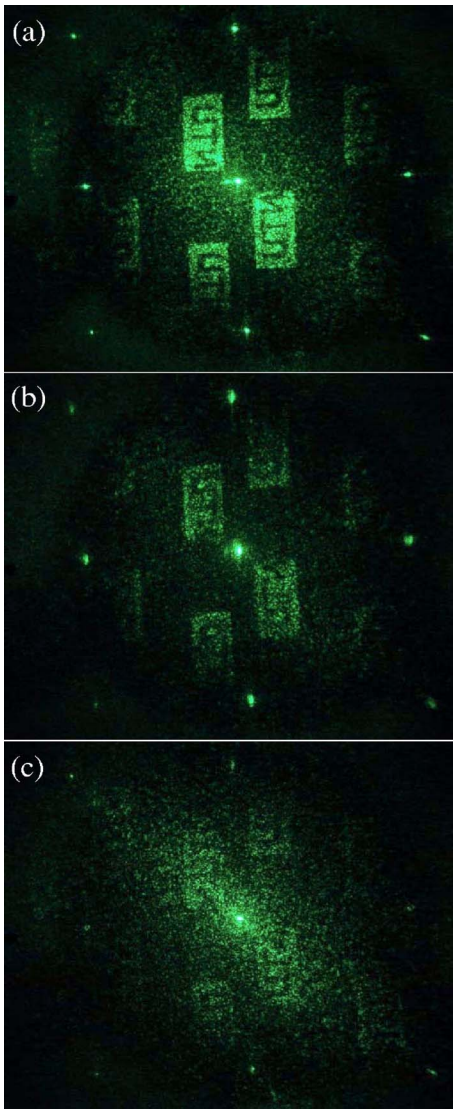

FIG. 4. (Color online) Photographs of the reconstructed CGHs at $V=0$ (a), $V=30$ V_{rms} (b), and $V=70$ V_{rms} (c), respectively.

Figure 4(a) shows the photograph of the reconstructed CGH without voltage applied. We can see a clear reversed NTU image from the photograph as a result of an inverted phase recorded in the PDLC film. The estimated diffraction efficiency is about 15%–20%, significantly less than the theoretical value (41%).[21] Figure 4(b) shows the reconstructed image with an applied voltage of 30 V_{rms}. It can be seen that the scattering loss reduces compared to Fig. 4(a), which may be induced by the optical clearing effect originated from LC droplet size distribution.[22] Figure 4(c) shows the case with a higher applied voltage of 70 V_{rms}. We can see from Fig. 4(c) that, the higher order diffractions become weak and more energy transfers to the 0th order. However, a larger scattering is induced by the index mismatch between the polymer and LC regions. Driven by a square wave of 50 V_{rms} with a frequency of 20 Hz, the electro-optical response of PDLC CGH was measured by an oscilloscope. In our experiment, the rising and falling times were about 1.54 and 1.92 ms, respectively, as shown in Fig. 5. This response time is slightly faster than that of the conventional LC SLM but slower than that of holographic PDLC.[16] However, the driving voltage

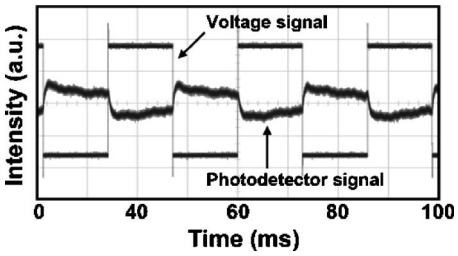

FIG. 5. Electro-optical response of the PDLC CGH driven by a square wave of 50 V_{rms}.

for our PDLC CGH (6 V/μm) is considerably smaller than that of holographic PDLC (20 V/μm).[23] Thus, our PDLC CGH has a good trade-off between driving voltage and response time.

Compared to a conventional method such as direct laser writing, the major advantages of our method are easy fabrication process, compactness, lightweight, and low cost. Moreover, the PDLC CGH is a write-once-read-many mode memory device and it is electrically switchable.

In conclusion, an electrically switchable phase-type CGH was fabricated using a PDLC material. With a suitable voltage applied, the reconstructed image can be erased due to the change of the refractive index difference between the polymer-rich and LC-rich regions. The results, though preliminary, show the possibility to record CGH in polymer/LC composite materials, which may lead to applications for PDLC in information storage and adaptive optical elements.

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[1] A. J. MacGovern and J. C. Wyant, Appl. Opt. **10**, 619 (1971).
[2] A. W. Lohman and D. P. Paris, Appl. Opt. **6**, 1739 (1967).
[3] O. Bryngdahl, Opt. Commun. **10**, 164 (1974).
[4] D. Casasent and C. Szczutkowski, Opt. Commun. **19**, 217 (1976).
[5] J. Cederquist and A. Tai, Appl. Opt. **23**, 3099 (1984).
[6] D. Casasent, Opt. Eng. (Bellingham) **24**, 724 (1985).
[7] K. Nakagawa, S. Iguchi, and T. Minemoto, Proc. SPIE **3470**, 77 (1998).
[8] L. Pugliese and G. M. Morris, Opt. Lett. **15**, 338 (1990).
[9] F. Guessous, T. Juchem, and N. Hampp, Proc. SPIE **5310**, 369 (2004).
[10] F. Mok, J. Diep, H.-K. Liu, and D. Psaltis, Opt. Lett. **11**, 748 (1986).
[11] V. Arrizon, L. A. Gonzalez, R. Ponce, and A. Serrano-Heredia, Appl. Opt. **44**, 1625 (2005).
[12] S. Zumer and J. W. Doane, Phys. Rev. A **34**, 3373 (1986).
[13] T. J. Bunning, L. V. Nararajan, V. P. Tondiglia, and R. L. Sutherland, Annu. Rev. Mater. Sci. **30**, 83 (2000).
[14] Y. J. Liu, B. Zhang, Y. Jia, and K. S. Xu, Opt. Commun. **218**, 27 (2003).
[15] Y. J. Liu, X. W. Sun, P. Shum, H. P. Li, J. Mi, W. Ji, and X. H. Zhang, Appl. Phys. Lett. **88**, 061107 (2006).
[16] V. P. Tondiglia, L. V. Natarajan, R. L. Sutherland, T. J. Bunning, and W. W. Adams, Opt. Lett. **20**, 1325 (1995).
[17] A. Emoto, H. Ono, and N. Kawatsuki, Liq. Cryst. **30**, 1201 (2003).
[18] A. Y.-G. Fuh, M.-S. Tsai, C.-Y. Huang, T.-C. Ko, and L.-C. Chien, Opt. Quantum Electron. **28**, 1535 (1996).
[19] Y. J. Liu, X. W. Sun, P. Shum, and X. J. Tin, Opt. Express **14**, 5634 (2006).
[20] R. W. Gerchberg and W. O. Saxton, Optik (Stuttgart) **35**, 237 (1972).
[21] J. A. Cox, T. Werner, J. Lee, S. Nelson, B. Fritz, and J. Bergstrom, Proc. SPIE **1211**, 116 (1990).
[22] Y. J. Liu and X. W. Sun, Appl. Phys. Lett. **89**, 171101 (2006).
[23] Y. J. Liu, X. W. Sun, J. H. Liu, H. T. Dai, and K. S. Xu, Opt. Mater. (Amsterdam, Neth.) **27**, 1451 (2005).