Colorized Magneto-optic Three Dimensional Display Using Optical Space Division Method

H. Takagi, K. Nakamura, K. Kudo, T. Goto, P. B. Lim, and M. Inoue

Toyohashi University of Technology, 1-1- Hibarigaoka, Tempaku, Toyohashi 441-8580, Japan

Holographic displays can represent real three-dimensional (3D) images. A key characteristic of holographic display is viewing angle. The viewing angle depends on the pixel size for showing holographic patterns. 3D holographic display with 1 μm pixel size can represent 3D images that viewing angle is over 30 degrees. We developed magneto-optic 3D display (3DMOSLM) with 1 μm magnetic pixel size by thermomagnetic recording method. However, this conventional 3DMOSLM could show only green and red colors because reference lights were only green and red colors. In addition, thickness of magnetic garnet films was designed for only green and red colors. In this study, we developed colorized 3DMOSLM using an optical space division method. The thickness of magnetic garnet films was designed for each color. The colorized 3DMOSLM could represent 3D images with blue, green and red colors.

Key words: Three dimensional display, colorization, magnetic hologram, magneto-optic effect, and thermomagnetic recording method

1. Introduction

In recent years, three-dimensional (3D) displays have demand from a lot of visualization technologies. However, conventional 3D displays need special glasses, and observation of 3D images should be from limited position. For these reasons, we developed 3D holographic display by thermomagnetic recording method (3DMOSLM). The holographic displays are expected to a realistic 3D display without special glasses because it produces an exact copy of scattered light wave front from an object [1-11]. In general, the 3D holographic display demands wide-viewing angles for 3D visualization. This viewing angle depends on pixel size for showing holographic patterns as follow:

\[ \theta = 2\sin(\frac{\lambda}{2p}), \quad (1) \]

where \( \theta \) is the viewing angle, \( \lambda \) is the wavelength, and \( p \) is the pixel size. The 3DMOSLM has magnetic garnet media with sub-micrometer magnetic pixel array for wide-viewing angle. The 3DMOSLM can represent real 3D image with high resolution, over 100 cd/m² brightness, and over 30 degrees viewing angle [12].

This conventional 3DMOSLM could show only green and red colors because reference lights were only green and red colors. In addition, thickness of magnetic garnet films was designed for green and red colors [13]. Full color displaying is necessity in a display technology. In this study, we developed colorized 3DMOSLM with blue, green, and red colors. The colorized 3DMOSLM has three magnetic garnet single-layered films that have high-diffraction efficiency for each color. The colorized 3DMOSLM used an optical space division method that can reconstruct the full-colored images by synthesizing reconstructed images of each color.

2. Magnetic garnet films for each color

A contrast and a light intensity of reconstructed 3D image depend on transmittance and Faraday rotation angle. In this study, the magnetic garnet single-layered film was yttrium iron garnet that substituted bismuth, dysprosium, and aluminum (BiDyYFeAlG). The BiDyYFeAlG film has high transmittance and large Faraday rotation angle on visible wavelength, and perpendicular magnetization. The optical characteristics of BiDyYFeAlG have wavelength dependence. Figure 1 shows calculated transmittance, Faraday rotation angle, and diffraction efficiency of BiDyYFeAlG. The calculation method was matrix approach method [14, 15]. The BiDyYFeAlG thickness was 1.0 μm. The diffraction efficiency in a magnetic hologram [16-19] was given in the following equation:

\[ \eta_{\text{diff}} = \left( \frac{4}{\pi \theta_p^2} \right) \cdot e^{-2\theta_p \sin^2(\theta_p t)}, \quad (2) \]

where \( \eta_{\text{diff}} \) is the diffraction efficiency, \( \alpha \) is absorption coefficient, \( t \) is thickness, \( \theta_p \) is Faraday rotation per unit film thickness. The diffraction efficiency is associated with a contrast and light intensity of reconstructed 3D images. The contrast of reconstructed 3D image depends on the transmittance and the squared quadrature component for incident light. For these reasons, we designed the thickness of BiDyYFeAlG films for each color. Figure 2 shows calculated diffraction efficiency versus thickness for each color. For blue color that is low diffraction efficiency, BiDyYFeAlG film thickness was selected local maximal value of diffraction efficiency. For green and red colors, BiDyYFeAlG thickness was decided by over 100 cd/m² brightness.
when a reference light intensity is 25.2 mW/cm$^2$, and maximum depth of thermomagnetic recording \cite{12,13}. Table 1 shows diffraction efficiency and thickness for each color. The diffraction efficiency is 0.19 $\times 10^{-2}$ % at 370 nm thickness for 450 nm wavelength, 2.81 $\times 10^{-2}$ % at 1,200 nm thickness for 532 nm wavelength, and 3.12 $\times 10^{-2}$ % at 2,600 nm thickness for 633 nm wavelength. The diffraction efficiency at 450 nm wavelength has extreme value, because the BiDyFeAlG has a large absorption of the light in blue wavelength range. In addition, Faraday rotation angle increases and transmittance decreases exponentially when the thickness increases. The ripple diffraction efficiency is caused by localized light effect between air and substrate. These designed BiDyYFeAlG films were fabricated by radio frequency ion beam sputtering. Table 1 shows characteristics of BiDyYFeAlG films. The diffraction efficiency of blue and green colors was almost the same with calculated values. BiDyYFeAlG film for red color has difference from calculated value because of composition difference.

3. Colorized 3D display using optical space division method

The colorized 3D-MOSLM used the optical space division method as shown in Fig. 3. The optical space division method can reconstruct full-colorized images by synthesizing reconstructed images of each color. This method uses some display media to show single color components of a full-colorized image. Figure 3 shows optical schematic of optical space division method. This optical system has three reference laser sources for each color, spatial filter for correcting beam shape, beam expander for expansion of display area, three BiDyYFeAlG films for each color, polarizers to obtain linearly polarized light and decrease intensity of $0^{th}$ transmitted light, charge-coupled device (CCD) with standard RGB (sRGB) for getting 3D images. The reference laser sources were CW lasers that maximum intensity was 1,120 $\mu$W at 450 nm, 160 $\mu$W at 532 nm, and 530 $\mu$W at 633 nm. The polarizers with cross-Nicol configuration can pass only diffracted light and cut no modulation $0^{th}$ transmitted light for clear reconstruction images, because the polarization angle of reconstructed light from magnetic hologram is rotated 90 degrees from incident light by magneto-optic effect. To evaluate gamut, we used a plate image. The plate image size was 2 $\times$ 2 mm$^2$ square. A distance between the BiDyYFeAlG film and the plate image was 20 mm. Each BiDyYFeAlG film had hologram patterns that

| Wavelength | R 633 nm | G 532 nm | B 450 nm | R 633 nm | G 532 nm | B 450 nm |
|------------|----------|----------|----------|----------|----------|----------|
| Thickness (nm) | 2600 | 1200 | 370 | 2600 | 1200 | 580 |
| Transmittance (%) | 69.9 | 24.9 | 13.9 | 59.9 | 40.0 | 6.1 |
| Faraday rotation angle (deg.) | 1.90 | 3.02 | 1.05 | 1.31 | 2.34 | 1.65 |
| Diffraction efficiency ($\times 10^{-2}$ %) | 3.12 | 2.81 | 0.19 | 1.25 | 2.70 | 0.21 |

Fig. 1 The transmittance, Faraday rotation angle, and diffraction efficiency versus wavelength of BiDyYFeAlG. The BiDyYFeAlG thickness was 1.0 $\mu$m.

Fig. 2 Diffraction efficiency by equation (2) versus thickness of BiDyYFeAlG for each color that is 450 nm, 532 nm, and 633 nm wavelength.

Table 1 Characteristics of BiDyYFeAlG films.
were 8.6 × 5.4 mm² for blue, 9.9 × 6.0 mm² for green, and 11.3 × 6.7 mm² for red. For writing a lot of magnetic pixels, we used a frame written laser system. The beam from a pulse laser (λ=532 nm, 10 nsec/pulse) passed a 2D hologram pattern positioned by a three-axis positioning stage. A light energy density was 150 mJ/cm² for writing magnetic pixels. A pixel size was about 1.36 μm on BiDyYFeAlG film.

Figure 4 shows gamut of reconstructed plate images at 0.4 × 0.4 mm² in 2 × 2 mm² from the 3D-MOSLM. Mono color of blue, green, or red was peak point of triangle, composition colors of two colors were on line of triangle, and composition colors of three colors were in triangle in Fig. 4. Gamut theoretical values were calculated by each reference light wavelength. The composition colors were represented by controlling intensity of each reference light. In the case of white color, theoretical light intensities of reconstructed image are blue: green: red = 0.66: 0.92: 1.00. The 3D-MOSLM represented white color plate image when reconstructed image intensities were blue: green: red = 0.70: 0.91: 1.00. Measurement points were in sRGB triangle because CCD was based on sRGB. As these results, the 3D-MOSLM could represent colorized 3D image.

For demonstration of the 3D-MOSLM, we reconstructed a 3D image with blue, green, and red colors. Fig. 5(a) shows the 3D image model that was three spheres of each color. The diameter of each sphere was 3.0 mm. The distance between each sphere and BiDyYFeAlG film was 20 mm. Hologram pattern was 8180 × 5,696 pixels in 11.1 × 7.7 mm² for 450 nm, 8,080 × 8,277 pixels in 11.0 × 11.3 mm² for 532 nm, and 9,560 × 6,099 pixels in 13.0 × 8.3 mm² for 633 nm. Reference light intensities were 441 μW at blue, 32 μW at green, and 216 μW at red. Fig. 5(b) shows reconstructed 3D spheres image. The 3D-MOSLM could represent colorized three spheres.

In this study, we developed the colorized 3D-MOSLM that was synthesized blue, green and red reconstructed images by the optical space division method. These results suggest that 3D-MOSLM can represent colorized 3D images.

4. Conclusion

The conventional 3D-MOSLM could show only green and red colors. However, the full color displaying is necessity in a display technology. In this study, we developed colorized 3D-MOSLM using the optical space division method. This optical system had three magnetic garnet films (BiDyYFeAlG) for each color. Thickness of BiDyYFeAlG films was designed by matrix approach method. The BiDyYFeAlG films had high-diffraction efficiency that were 0.19 × 10⁻² % at 370 nm thickness for 450 nm, 2.81 × 10⁻² % at 1,200 nm thickness for 532 nm, and 3.12 × 10⁻² % at 2,600 nm thickness for 633 nm.

For visualization of colorized 3D images, we used the optical space division method that compounded images of each color in sRGB reconstructed from the BiDyYFeAlG films. The 3D-MOSLM could represent colorized 3D image that is necessity character in display technology.

Fig. 3 Optical schematic of optical space division method.

Fig. 4 Color gamut mapping of colorized 3D-MOSLM. (a) Plate image model for evaluation color gamut, (b) color gamut mapping.
**Fig. 5 Colorized 3D image with 3D-MOSLM. (a) 3D image model, (b) reconstructed 3D image.**

**Acknowledgements** This work was supported by Grant-in-Aid for Young Scientists (B) 25820124.

**References**

1) D. Gabor: *Nature*, 161, 777 (1948).
2) P. Hilaire, S. Benton, M. Lucente: *J. Opt. Soc. Am. A.*, 9, 1969 (1992).
3) F. Mok, J. Diep, H. K. Liu, D. Psaltis: *Opt. Lett.*, 11, 748 (1986).
4) K. Maeno, N. Fukaya, O. Nishikawa, K. Sato: *Proc. SPIE*, 2652, 13 (1996).
5) M. Stanley, R. Bannister, C. Cameron, S. Coomber, I. Cresswell, J. Hughes, V. Hui, P. Jackson, K. Milham, R. Miller, D. Payne, J. Quarrel, D. Scatteringood, A. Smith, M. Smith, D. Tipton, P. Watson, C. Slinger: *Proc. SPIE*, 5008, 247 (2003).
6) Y. Takaki, Y. Tanemoto: *Opt. Express*, 18, 10294 (2010).
7) T. Kozacki, G. Finke, P. Garbat, W. Zaperty, M. Kujawińska: *Opt. Express*, 20, 27473 (2012).
8) Y. Z. Liu, X. N. Pang, S. Jiang, J. W. Dong: *Opt. Express*, 21, 12068 (2013).
9) T. Mishina, F. Okano and I. Yuyama: *Appl. Opt.*, 38, 3703 (1999).
10) T. Senoh, T. Mishina, K. Yamamoto, T. Kurita, *J. Display Tech.*, 7, 382 (2011).
11) K. Aoshima, N. Funabashi, K. Machida, Y. Miyamoto, K. Kuga, T. Ishibashi, N. Shimidzu, F. Sato, *J. Display Tech.*, 6, 374 (2010).
12) H. Takagi, K. Nakamura, T. Goto, P. B. Lim, M. Inoue: *Opt. Lett.*, 35, 3344 (2014).
13) K. Nakamura, K. Kudo, T. Goto, H. Takagi, P. B. Lim, M. Inoue, *IEEE Trans on Magn.*, in press.
14) M. Inoue, R. Fujikawa, A. Barishev, A. Khanikaev, P. B. Lim, H. Uchida, O. Aktsipetrov, A. Fedyanin, T. Murzina, A. Granovsky: *J. Phys. D.*, 39, R151 (2006).
15) M. Inoue, T. Fuji: *J. Appl. Phys.*, 81, 5659 (1997).
16) H. Haska: *IEEE Trans. Magn.*, 6, 542 (1970).
17) G. Fan, K. Pennington, J. H. Greiner: *J. Appl. Phys.*, 30, 974 (1969). Magnetic hologram
18) R. S. Mezrich: *Appl. Phys. Lett.*, 15, 132 (1969).
19) J. P. Waters: *Appl. Phys. Lett.*, 9, 405 (1966).

Received Oct. 21, 2014; Accepted Jan. 14, 2015