Magnetic Hologram Reconstruction Using Magneto-Optical Light Modulator Array Based on Domain Wall Motion

Ryo Higashida, Nobuhiko Funabashi, Ken-ichi Aoshima and Kenji Machida

NHK, 1-10-11, Kinuta, Setagaya-ku, Tokyo 157-8510, Japan
Keywords: electro-holography, spatial light modulator, magneto-optical effects, domain wall motion

ABSTRACT

A magneto-optical light modulator array capable of displaying a magnetic interference pattern by the application of an external magnetic field was fabricated. This array showed that magneto-optical spatial light modulator based on current-induced domain wall motion has sufficient light-modulation characteristics for reconstructing holographic images.

1 INTRODUCTION

Many studies on holographic displays using a spatial light modulator (SLM) have been reported for dynamic holographic three-dimensional (3D) image reconstruction [1,2]. The viewing-zone angle of the holographic image reconstructed by the holographic display is given by equation (1).

$$\phi = 2\,sin^{-1}\frac{\lambda}{2d} \quad (1)$$

where Φ is the viewing-zone angle, λ is the wavelength of incident light, and d is the pixel pitch of the SLM. The smallest pixel pitch of a commercially available SLM is approximately 4 μm [3], with insufficient viewing-zone angle.

We have developed an SLM using magneto-optical effects (MO-SLM), which is expected to reduce the pixel pitch to the submicron scale for holographic displays with a wide viewing-zone angle [4-6]. In the MO-SLM, each pixel comprises a fine magnet, and the magnetization direction of each pixel is controlled electrically. We proposed a new type of MO-SLM based on current-induced domain wall motion (CIDWM) [7-9], which can reverse the magnetization direction by low driving current, and successfully demonstrated the operation of a basic device corresponding to one pixel [10,11].

Light-modulation characteristics of MO devices with complicated pixel structures, such as the CIDWM-based MO-SLM, have not been studied sufficiently. In general, magneto-optical effects modulate light only to a small extent. Moreover, in our SLM, the aperture area is limited by pixel structure. Therefore, it should be ensured that the device has sufficient light-modulation characteristics for reconstructing holographic images.

In this work, we fabricated an MO light modulator array that can display a magnetization interference pattern by applying an external magnetic field as an evaluation device and demonstrated the reconstruction of a hologram by MO effects.

2 METHODS

2.1 Spatial Light Modulator Based on Current-Induced Domain Wall Motion

Figure 1 shows the structure of a CIDWM-based MO-SLM. Each pixel consists of a magnetic nanowire for light modulation and two nanomagnets (NMs): NM1, NM2 for controlling the switching properties of the nanowire. The magnetization direction of the light modulation region is controlled by injecting current that is supplied from a cell selection transistor based on CIDWM. When linearly polarized light enters the device, the polarization plane of the reflected light rotates in accordance with the magnetization direction of the light modulation region by MO effects. The magnetic hologram [12,13] reconstructs the holographic image by displaying an interference pattern based on the magnetization direction.

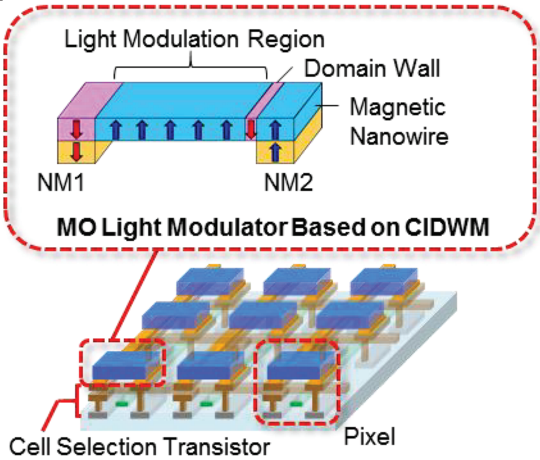

Fig. 1 Structure of the CIDWM-based MO-SLM

Figure 2 shows a cross-sectional illustration of a pixel fabricated on a thermally oxidized silicon wafer substrate without a cell selection transistor. The NM material [Co(0.3 nm)/Pd(0.6 nm)]$_{25}$ was deposited on the substrate at room temperature using a helicon sputtering system. The NMs were fabricated using electron beam lithography, ion beam milling, SiO_2 and Si_3N_4 deposition, and a lift-off process. The nanowire material $Gd_{24}Fe_{76}$ alloy was deposited on the NMs by ion beam sputtering, and Si_3N_4 was deposited on the $Gd_{0.24}Fe_{0.76}$ alloy by radio frequency sputtering as a cap layer. The light modulation nanowire was fabricated by using the same process as that used for the NMs. These processes are the same as the fabrication processes of the device in a previous study that successfully demonstrated current injection [11].

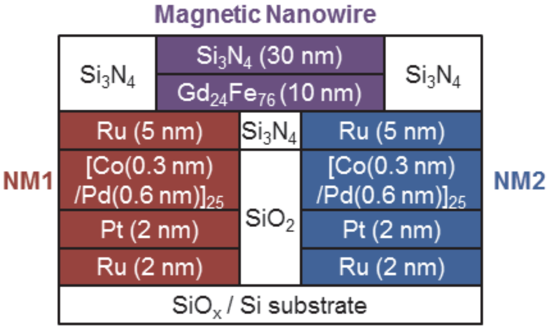

Fig. 2 Cross-sectional illustration of the pixel without a cell selection transistor

2.2 Display Magnetization Pattern by Applying External Magnetic Field

In this paper, we utilize a characteristic whereby the magnetization reversal mechanism of the light modulation region changes with the existence of the NM used for displaying magnetization patterns. Figure 3 (a) shows a device with two NMs; here the magnetization direction of the light modulation region is easily reversed by applying an external magnetic field. Figure 3 (b) shows a device with only one NM; here it is difficult to reverse the magnetization direction of the light modulation region on one side of the external magnetic field. The magnetization pattern was displayed by fabricating two NMs on the pixel to be reversed and applying an appropriate external magnetic field.

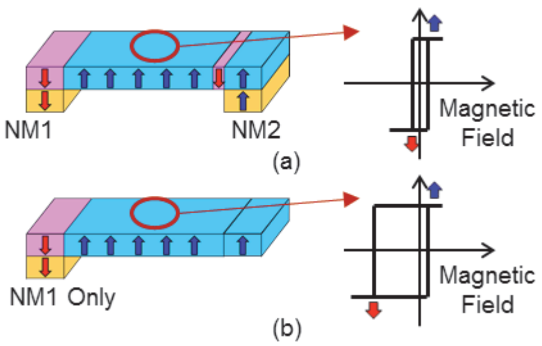

Fig. 3 Difference in magnetization reversal mechanism of the light modulation region (a) with and (b) without NMs

3 RESULTS & DISCUSSION

Figure 4 shows the design of an MO light modulator array with a 1 × 2 μm pixel pitch to obtain a large horizontal parallax. By sharing some components between adjacent pixels, the fabrication process is reduced and the aperture ratio is improved [11].

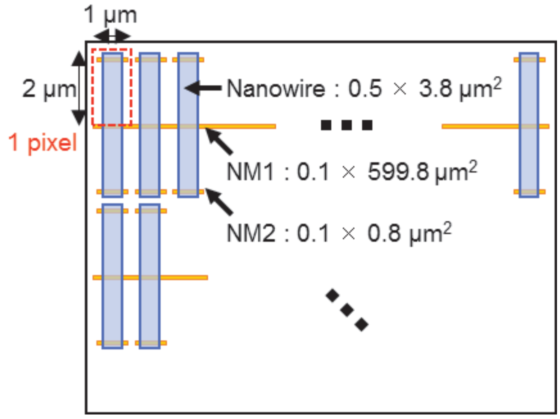

Fig. 4 Design of the MO light modulator array

The binary interference pattern displayed on the array was calculated by computer-generated holography (CGH) using Fresnel diffraction. The arrangement of a 3D object is shown in Figure 5. Two planes of a cube on which the Japanese character “i” is fixed were displayed 0.5 mm behind the hologram. Table 1 lists the calculation parameters for CGH.

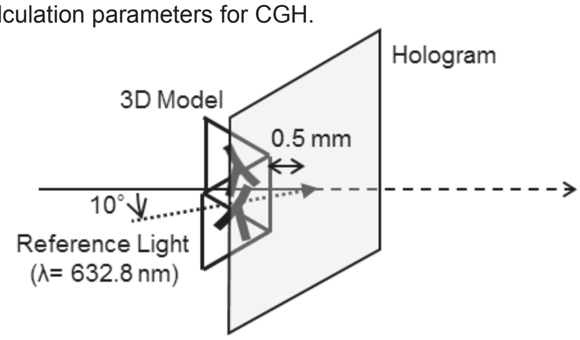

Fig. 5 Arrangement of a 3D object

Table 1 Calculation parameters for CGH

Pixel number	10k × 10k
Pixel pitch	1 × 2 μm
Hologram size	10 × 20 mm
Wavelength	632.8 nm

A 10k × 10k MO light modulator array was fabricated with NM2 in the white pixel of the interference pattern. The interference pattern was displayed by applying an external magnetic field of −0.1 kOe.

Figure 6 shows a schematic illustration of the optical system for holographic image reconstruction. A He-Ne laser (λ = 632.8 nm) was used as a light source. An expanded and polarized laser beam entered the array as reproducing illumination light. An electromagnet was set behind the array to turn on/off the magnetic interference pattern by applying an external magnetic field. A reconstructed holographic image was captured by a camera with the analyzer to eliminate noise light.

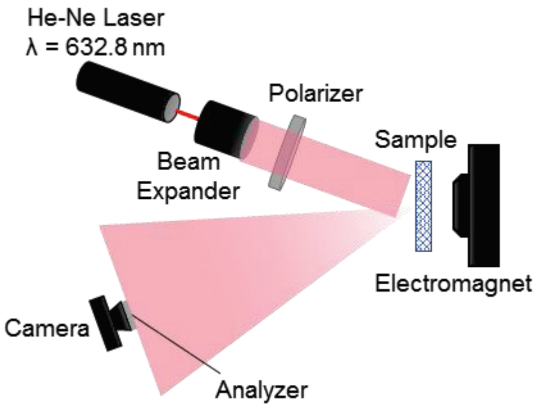

Fig. 6 Schematic illustration of the optical system for holographic image reconstruction

Figure 7(a) shows the reconstructed holographic 3D image obtained by applying an external magnetic field of −0.1 kOe. Our device demonstrated sufficient light-modulation performance for holographic image reconstruction. It was also confirmed that when the magnetic interference pattern was not displayed by applying an external magnetic field of +0.1 kOe, the holographic image was not reconstructed, as shown in Figure 7(b).

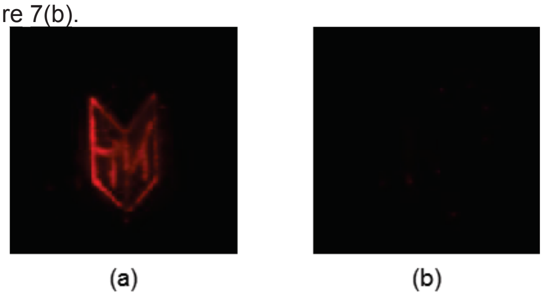

Fig. 7 Reconstructed holographic 3D image by applying an external magnetic field of (a) −0.1 kOe (ON) and (b) +0.1 kOe (OFF)

4 CONCLUSIONS

To investigate the light-modulation characteristics of a CIDWM-based MO-SLM, an MO light modulator array was fabricated, and the magnetization direction of the pixel with NMs was reversed by applying the appropriate external magnetic field. A 10k × 10k light modulator array capable of displaying a magnetic interference pattern was fabricated, and a reconstruction of the holographic 3D image was successfully demonstrated. Therefore, if this structure is fabricated on cell selection transistors and an arbitrary magnetization pattern can be displayed by current injection, a dynamic holographic image can be reconstructed.

REFERENCES

[1] N. Hashimoto, S. Morokawa, and K. Kitamura, "Real-time Holography Using the High-Resolution LCTV-SLM," Proc. SPIE, vol. 1461, pp. 291–302 (1991).
[2] K. Maeno, N. Fukaya, and O. Nishikawa, "Electro-holographic Display Using 15 Mega Pixels LCD," Proc. SPIE, vol. 2652, pp. 15–23 (1996).
[3] Holoeye GAEA 2, Retrieved September 17, 2019, from https://holoeye.com/gaea-4k-phase-only-spatial-light-modulator/
[4] K. Aoshima, N. Funabashi, K. Machida, Y. Miyamoto, K. Kuga, T. Ishibashi, N. Shimidzu, and F. Sato, "Submicron Magneto-Optical Spatial Light Modulation Device for Holographic Displays Driven by Spin-Polarized Electrons," J. Display Technol. vol. 6, no. 9, pp. 374–380 (2010).
[5] H. Kinjo, K. Aoshima, N. Funabashi, T. Usui, S. Aso, D. Kato, K. Machida, K. Kuga, T. Ishibashi, and H. Kikuchi, "Two Micron Pixel Pitch Active Matrix Spatial Light Modulator Driven by Spin Transfer Switching," Electronics vol. 5, p. 55 (2016).
[6] K. Aoshima, H. Kinjo, K. Machida, D. Kato, K. Kuga, T. Ishibashi, and H. Kikuchi, "Active Matrix Magneto-Optical Spatial Light Modulator Driven by Spin-Transfer-Switching," J. Display Tech. vol. 12, pp. 1212–1217 (2016).
[7] A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, "Real-Space Observation of Current-Driven Domain Wall Motion in Submicron Magnetic Wires," Phys. Rev. Lett. vol. 92, p. 077205 (2004).
[8] S. S. P. Parkin, M. Hayashi, and L. Thomas, "Magnetic Domain-Wall Racetrack Memory," Science vol. 320, pp.190–194 (2008).
[9] M. Hayashi, L. Thomas, R. Moriya, C. Rettner, and S. S. P. Parkin, "Current Driven Domain Wall Velocities Exceeding the Spin Angular Momentum Transfer Rate in Permalloy Nanowires," Phys. Rev. Lett. vol. 98, p. 037204 (2007).
[10] K. Aoshima, R. Ebisawa, N. Funabashi, K. Kuga, K. Machida, "Current-induced Domain-Wall Motion in Patterned Nanowires with Various Gd–Fe Compositions for Magneto-optical Light Modulator Applications," Jpn. J. Appl. Phys. vol. 57, p. 09TC03 (2018).
[11] R. Higashida, N. Funabashi, K. Aoshima, and K. Machida, "A Current Induced Domain Wall Motion Type Light Modulation Device for Electro-Holography," Joint MMM-Intermag. GN-02 (2019).
[12] R. S. Mezrich, "Reconstruction Effects in Magnetic Holography," IEEE Trans. Magn. vol. 6, pp. 537–541 (1970).
[13] H. M. Haskal, "Polarization and Efficiency in Magnetic Holography," IEEE Trans. Magn. vol. 6, pp. 542–545 (1970).