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Fomation and Properties of Multiple-Tone Spatial Light Modulator using Garnet Film with In-Plane Magnetization

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We attempted to fabricate a new type of magneto optic spatial light modulator (MO-SLM) for multiple-tone modulation by using in-plane magnetization. In the MO-SLM, magnetic property of magneto-optical layer was modified to be suitable for multiple-tone expression by substituting Al in Bi:YIG film. At a driving current to 28 mA in an electrode of the fabricated MO-SLM, changes in brightness of pixels were observed using a polarization microscope.

Key words : magneto-optic spatial light modulator, MO-SLM, multiple-torn, garnet, magneto optical effect

1. Introduction

Since optical communication technology progressed remarkably in recent years, developments of new optical devices are being expected. A spatial light modulator (SLM) is one of prospective optical devices, because the SLM can treat large amount of data as a page with two-dimensional array. A representative SLM is a liquid crystal SLM, however, it has disadvantage of slow switching speed of several kHz. A solution that improves switching speed is to achieve a magneto-optic spatial light modulator (MO-SLM), which modulates plane of polarized light using magneto-optical effect. The previously reported MO-SLMs included a magnetic garnet film with out-of-plane magnetic anisotropy, so magnetization of the garnet film was controlled in the out-of-plane direction. Therefore, the MO-SLMs can modulate lights as binary information [1-4].

In the article, we attempted to fabricate a new type of MO-SLM for two-dimensional page data with multiple-tone. By developing the multiple-tone MO-SLM, we can treat large amount and analog information with high speed. Appearance of the multiple-tone MOSLM will have great influence in the field of optical information technology, such as light computing, projector and holographic recording.

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2. Principle of multiple-tone MO-SLM

A MO-SLM (Fig. 1(a)) consists of magneto-optical layer for pixels, and electrodes for flowing current to make magnetic field. The MO-SLM utilizes magneto optical Faraday effect, so that rotation direction of plane of polarized light changes by direction of magnetization. The Faraday rotation angle θ_F in the magneto-optical layer is given as

$$\theta_F = F(M/Ms)l, \quad (1)$$

where F is Verde constant, M is magnetization, Ms is saturation magnetization, and l is thickness of the magneto-optical layer. Intensity I of the transmitted light from the MO-SLM is described by

$$I = \cos\theta, \quad (2)$$

where θ is angular difference of the plane of polarized light to polarizer.

In previously reported conventional MO-SLMs [1-3] (Fig. 1(b)), the magneto-optical Bi:YIG layer was formed by liquid phase epitaxy (LPE), whose Bi:YIG film had easy axis of out-of-plane magnetization. Therefore, direction of magnetization of magneto-optical Bi:YIG layer switched vertically to the film, which was the same direction of transmitted light. So, the conventional MO-SLM

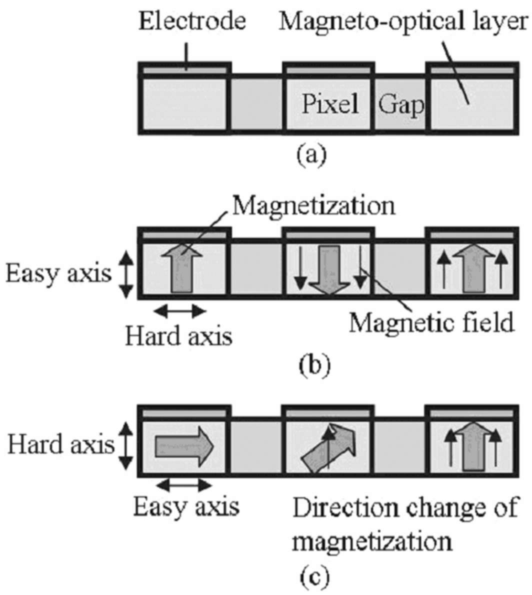

Fig. 1. Principle of operation of MO-SLM having a magneto-optical Bi-YIG film. (a) Basic structure of a MO-SLM, (b) a conventional MO-SLM using out-of-plane magnetization, and (c) a multiple-tone MO-SLM using in-plane magnetization.

changed contrast of light as binary information by changing magnetization.

The multiple-tone MO-SLM (Fig. 1(c)) uses a poly-crystalline garnet film as a magneto-optical layer with in-plane magnetization. Principle of operation of this MO-SLM is to make the direction of magnetization change gradually from in-plane to out-of-plane, so intensity of light would be controllable as expressed by the equation (1).

3. Design and Fabrication of the Multiple-tone MO-SLM

3.1. Magneto-optical Bi,Al:YIG layer

Base of the magneto-optical layer of the multiple-tone MO-SLM with in-plane magnetization was Bi substituted yttrium iron garnet (Bi:YIG) film fabricated by RF magnetron sputtering method, since the Bi:YIG film has shape anisotropy, that is, easy axis of in-plane magnetization. In order to modify magnetic property, we used Al substituted Bi:YIG film (Al,Bi:YIG) by using Al_2O_3 pellets on a $Bi_{1.0}Y_{2.5}Fe_5O_x$ target in RF magnetron sputtering method. Fabrication condition of sputtering process is shown in Table 1. After the film deposition, the amorphous film was crystallized by annealing in atmosphere. By substitution of Al^{3+} ions for Fe^{3+} ions in crystallographic YIG structure, the saturation magnetization was decreased. The Bi,Al:YIG film with low saturation magnetization

Table 1. Fabrication condition of RF magnetron sputtering

Film	Bi,Al:YIG
Target	Al_2O_3 pellets on $Bi_{1.0}Y_{2.5}$
Sputtering gas	Ar:6.3 ccm
Sputtering pressure	3 mTorr
Substrate temperature	100 °C
Sputtering power	100 W

has advantage of operation of the multiple-tone MO-SLM that controls the light by an applied magnetic field using a current.

3.2. Fabrication process of the multiple-tone MO-SLM

Fig. 2 shows fabrication process of the multiple-tone MO-SLM using in-plane magnetization. First, as shown in Fig. 2(a) we prepared the Bi,Al:YIG composition amorphous film with thickness of 1 μm on the Corning #1737 glass. Then, photoresist masks of pixels were formed by photolithography on the Bi,Al:YIG composition film (Fig. 2(b)); the film was etched by phosphoric acid to separate pixels (Fig. 2(c)) because of magnetic isolation of pixels. After the photoresist masks were removed by acetone, the Bi,Al:YIG composition pixels were annealed for crystallization at 750°C for 15 minutes in the atmosphere in an electric furnace (Fig. 2(d)). After

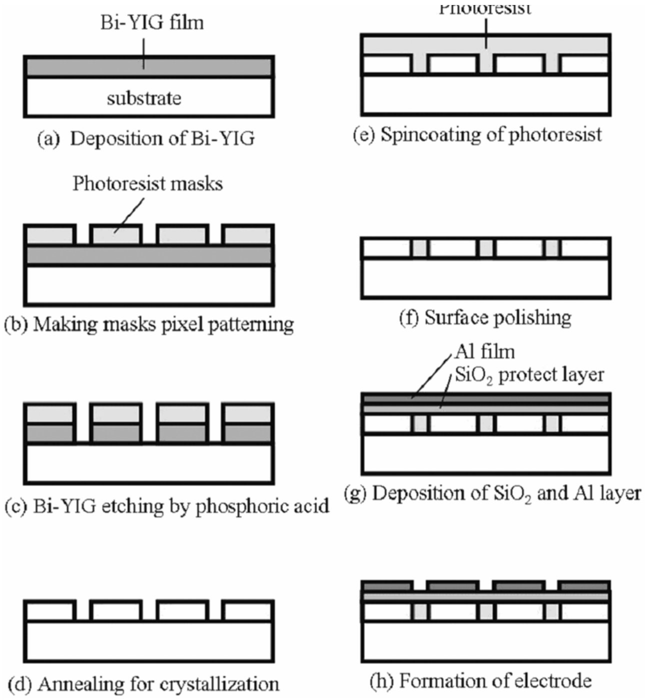

Fig. 2. Fabrication process of the multiple-tone MO-SLM using in-plane magnetization.

the Bi,Al:YIG pixels were coated by photoresist by a spin coater (Fig. 2(e)), the photoresist was polished to make smooth surface (Fig. 2(f)). To prevent detachment of the photoresist, SiO_2 film with thickness of 400 nm was deposited by RF magnetron sputtering method as a protection layer. Then, an Al film for electrode was deposited on the SiO_2 film (Fig. 2(g)) by sputtering method; finally Al electrodes were formed by the photolithography (Fig. 2(h)).

4. Results and Discussion

4.1. Magneto-optical Bi,Al:YIG layer

In the magneto-optical Bi:YIG layer, changing Al substitution ratio, magnetic properties of the garnet film can be modified to be suitable for multiple-tone modulation. Fig. 3 shows magnetic properties of Bi,Al:YIG fabricated by using the Al_2O_3 pellets on the $Bi_{1.0}Y_{2.5}Fe_5O_x$ target. As the Al substitution increases, the saturation magnetization and saturation magnetic field decreased, and coercivity increased.

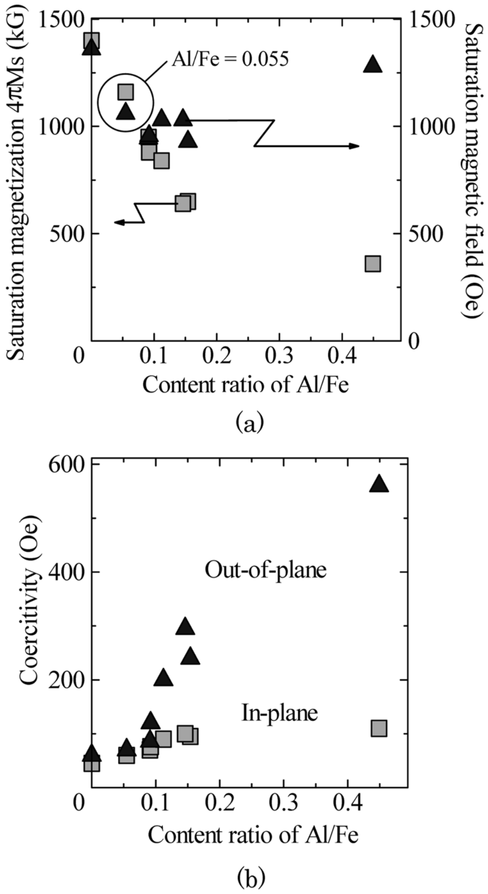

Fig. 3. (a) Saturation magnetization and saturation magnetic field, and (b) coercivity of the Bi,Al:YIG film as a function of Al/Fe ratio.

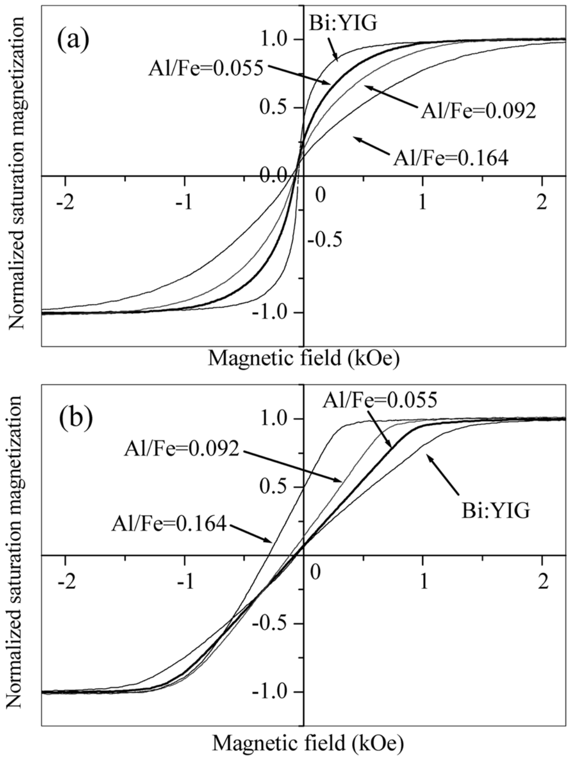

Fig. 4. Magnetization curves normalized by saturation magnetization for (a) in-plane and (b) out-of-plane directions.

Fig. 4 shows magnetization curves normalized by the saturation magnetization for (a) in-plane and (b) out-of-plane magnetizations. With increasing Al substitution, saturation magnetic field for in-plane increased, but saturation magnetic field for out-of-plane decreased. That is, magnetic anisotropy changed to a small degree. From the results of the experiments for Al substitution as shown in Fig. 3 and 4, we selected Al/Fe content ratio of 0.055 because of low saturation magnetic field, small magnetic anisotropy.

4.2. Structure of the multiple-tone MO-SLM

Fig. 5 shows photograph of the fabricated multiple-tone MO-SLM. The size of pixel was 16 μm, gap of pixels was 2 μm, and width of Al electrode was 4 μm. The shape of electrode was U type. Since it is the prototype device to confirm the principle of operation, only horizontal electrodes were formed. In the magneto-optical Bi,Al:YIG layer, the Al/Fe content ratio was 0.055. The separation of pixels makes cracks of the Bi,Al:YIG film decrease during annealing process by different thermal expansion coefficient between the Bi,Al:YIG film and the glass substrate.

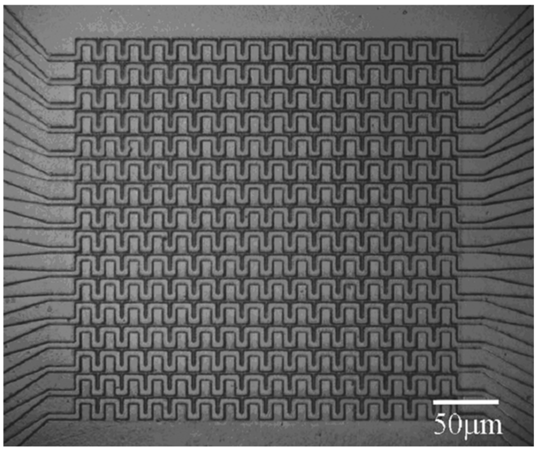

Fig. 5. Photograph of the fabricated multiple-tone MO-SLM.

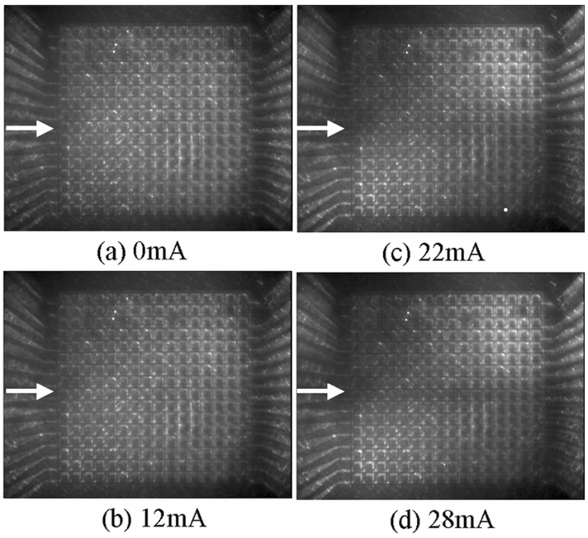

Fig. 6. Images of polarization microscope of the multiple-tone MO-SLM. Arrows indicates a line flowing a driving current

4.3. Magneto-optical evaluation

Fig. 6 shows images of polarization microscope of the fabricated multiple-tone MO-SLM. Arrows indicates a line of pixels with an electrode flowing a driving current. When a driving current was changed from 0 to 28 mA, brightness of magneto-optical images changed as seen from Fig. 6(a) to (d). Therefore, we confirmed that the MO-SLM was able to control light in selected pixels by changing the magnetization from in-plane direction to out-of-plane direction. However, the electrode of the MO-SLM disconnected by a current above 28 mA. So, it must be solved this heating problem by decrease of electric resistance of the electrode, by design of electrode pattern for effective magnetic field and so on, in order to obtain of the applicative multiple-tone MO-SLM.

5. Conclusion

We fabricated the prototype multiple-tone MO-SLM using in-plane magnetization. As the magneto-optical layer, we used Bi,Al:YIG film deposited by RF magnetron sputtering method in order to modify the magnetic properties for being multiple-tone modulation. By using the polarization microscope, change of brightness in images was observed when the current flowed from 0 mA to 28 mA. Therefore, the principle of operation as the multiple-tone MO-SLM was confirmed as the magnetization of the Bi,Al:YIG layer changed from the in-plane direction to the out-of-plane one.

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