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Three-dimensional Nanostructuring in YIG Ferrite with Femtosecond Laser

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Abstract: We demonstrated forming nanostructures inside a substrate of cerium-substituted yttrium iron garnet by means of direct laser writing. The laser irradiation increases a refractive index by 0.7% and changes magnetic properties from hard to soft.

OCIS codes: (350.3390) Laser materials processing; (320.2250) Femtosecond phenomena

1. Introduction

Cerium-substituted yttrium iron garnet ($Ce_xY_{3-x}Fe_5O_{12}$: Ce:YIG) is a ferrimagnetic ceramic material with a large Faraday rotation and high transparency for infrared light wavelengths over 600 nm [1]. Because of these strong figures of merit, Ce:YIG has been widely used for Faraday rotators, microwave filters, and various nonlinear optical devices. In addition to these existing applications, Ce:YIG can be used to make non-reciprocal waveguide devices to break the time-reversal symmetry of light propagation in photonic integrated circuits (PICs) [2]. Although Ce:YIG has many potential applications in PICs, it is not very compatible with PICs. To make functional PICs, we had to join many Ce:YIG elements with semiconductor waveguides on PICs. However, existing YIG joining uses either an adhesive agent or plasma-assisted direct bonding [3], and neither of these is sufficient for mechanical, chemical, and thermal durability. To make reliable PICs, we have to decrease the number of joined parts and therefore decrease the number of YIG elements. So, let us consider incorporating two or more YIG elements together with attached optical waveguides into a piece of YIG material. For this purpose, here we report a three-dimensional (3D) nanostructuring of Ce:YIG with a femtosencond laser.

Direct 3D writing with intense femtosecond laser pulses has been used to form nanostructures in transparent materials such as glasses and polymers [4]. In this paper, we apply this technology to ferrimagnetic ceramic materials, using Ce:YIG as an example [5]. We show that laser irradiation of Ce:YIG modifies both the optical and magnetic properties of the irradiated areas. Because of the nonlinear multiphoton-absorption process, the modification occurs only at the focusing voxel, and we can form submicron-scaled 3D nanostructures with varying optical and magnetic properties.

2. Change in optical property of Ce:YIG after laser irradiation

Figure 1(a) shows a Ce:YIG wafer we used for the experiment. A 1.2-μm-thick magneto-optical single-crystalline Ce:YIG layer is grown on a (111)-oriented nonmagnetic garnet substrate ($(GdCa)_3(GaMgZr)_5O_{12}$ or SGGG) using magnetoron sputtering epitaxy. The grown Ce:YIG layer had a mirror-like surface with a yellowish green color and a relative refractive index of 2.2. It exhibited a weak coercive force of 30 Oe.

The light source for direct laser writing was a mode-locked Ti:sapphire laser with an 800-nm wavelength, 80-fs pulse width, and 82-MHz repetition rate. The laser beam was focused in the Ce:YIG layer, using an objective lens with a numerical aperture of 0.9, so that the two-photon absorption would occur at the focusing voxel in the Ce:YIG layer. Figure 1(b) shows the line patterns observed with phase-contrast microscopy. In this example, we wrote five single-pass lines **a**-**e** with different laser powers and a multi-pass line

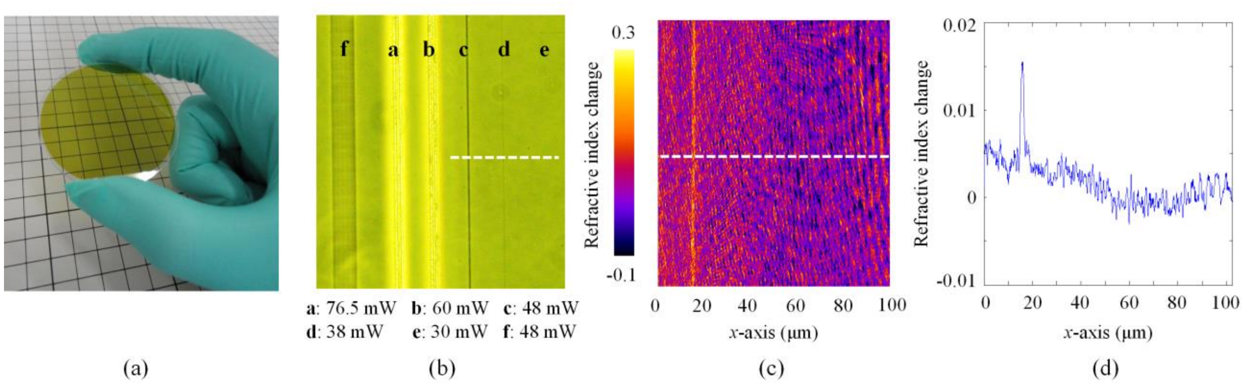

Fig. 1. (a) Epitaxial ferrimagnetic Ce:YIG layer grown on a (111)-oriented nonmagnetic garnet (SGGG) substrate. (b) Plane view of lines in Ce:YIG layer written with different laser powers, observed with phase-contrast microscopy. One multi-pass line **f** and five single-pass lines **a-e** are written, but some of them cannot be observed (see text). (c) Distribution of refractive-index change observed with quantitative phase imaging. (d) Change in refractive index along the dashed lines in (c).

f consisting of 20 single-pass lines. The laser power ranged from 30-76.5 mW at the entrance pupil of the objective for the five single-pass lines and was held at 48 mW for the multi-pass line. The scanning speed of the laser beam was set to 100 μm/min. We found that a laser power of 60 mW or higher caused thermal cracks to the Ce:YIG layer. This is shown in Fig. 1(b) by the two yellow stripes. At moderate powers, the laser writing changed the optical property of Ce:YIG without any cracking, and this can be observed by two thin lines (**c** and **d**) in Fig. 1(b). The width of the line was 1.5 μm for 48 mW and 750 nm for 38 mW. For laser powers of 30 mW or lower, we couldn't discern any remarkable changes in the optical properties.

Laser irradiation changed the refractive index of the Ce:YIG layer. We measured the change by means of quantitative phase imaging (QPI). The QPI is a technology, based on optical interferometry, to measure the image (or map) of path-length shifts associated with the specimen [6]. Using QPI information for the irradiated Ce:YIG/SGGG wafer, we have quantified the intracrystal refractive index. Figure 1(c) shows the profile of the changes around the laser-written lines. Laser irradiation increased the refractive index of the Ce:YIG layer. The increment, measured at a wavelength of 632.8 nm, was 0.015±0.001 (0.7% of Ce:YIG refractive index) for the line created with a 48-mW laser power and 100-μm/min scanning speed (see Fig. 1(d)).

3. Change in magnetic property of Ce:YIG after laser irradiation

A significant goal in this study is to show that, unlike other transparent materials such as glasses and polymers, it is possible to control both the magnetic properties and the refractive index of the Ce:YIG layer. To confirm this, we measured the effect of laser irradiation on the magnetization of the Ce:YIG layer. To see the magnetic-domain configuration in the Ce:YIG layer, we made use of the magneto-optical polar Kerr effect (MOKE). Figures 2(a)–2(f) show the MOKE images measured for a sample of Ce:YIG layer with laser-written lines. For reference, Fig. 2(g) shows a phase-contrast microscope image of the same sample. The MOKE images were taken using light from a mercury lamp at room temperature with an external magnetic field (parallel to the surface layer). The dark regions are positively magnetized, and the light regions are negatively magnetized.

First, we measured the sample with increasing the magnetic field from -500 Oe to 500 Oe. At an external magnetic field of -470.7 Oe, the entire Ce:YIG layer was negatively magnetized (Fig. 2(a)). Thus, the Ce:YIG layer, including irradiated regions, was magnetized in the same direction as the magnetic field. As magnetic field increased in the positive direction, the MOKE images changed as shown in Figs. 2(b) and 2(c). The irradiated regions easily changed their magnetization in response to the external magnetic field. (The upper two lines are ignored because they are dislocated regions with cracks.) In contrast, the non-irradiated regions tended to maintain their magnetization. At an external magnetic field of 495 Oe, the entire Ce:YIG layer was positively magnetized (Fig. 2(d)). After that, we measured the layer with sweeping the magnetic field from the positive side (500 Oe) to the negative side (-500 Oe) and observed that the domain showed a hysteretic cycling as shown in Figs. 2(e) and 2(f).

Figure 2(h) shows the schematic magnetization (M-H) curve of the Ce:YIG layer calculated from the measured domain configurations. The blue curve is for the irradiated region, and the red curve is for the non-irradiated region (This M-H curve is given simply to assist the understanding of the magnetic properties measured with MOKE imaging. More precisely, it is necessary to measure the magnetization curve for local nanometer regions.) Points a-f on the curves correspond to MOKE images (a)-(f), respectively. The laser irradiation changes the magnetic property of the Ce:YIG layer from hard to soft. In this way, we can achieve local control of the magnetization inside the Ce:YIG layer using laser irradiation.

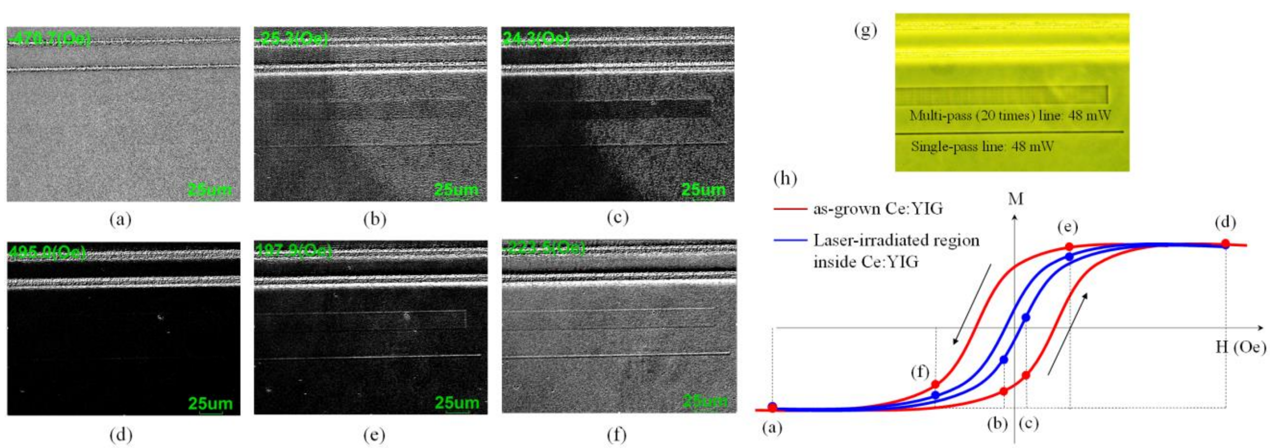

Fig. 2. Effect of laser irradiation on magnetization. (a-f) Magneto-optical polar-Kerr-effect images of the sample at room temperature. The dark regions are positively magnetized, and the light regions are negatively magnetized. Each figure shows the domain configurations under an external magnetic field of (a) -470.7 Oe, (b) -25.3 Oe, (c) 24.3 Oe, (d) 495 Oe, (e) 197.9 Oe, and (f) -223.5 Oe. (g) Phase-contrast microscope image of the same sample. (h) Schematic magnetization curve of Ce:YIG layer with and without irradiation.

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