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All-optical reversible switching of local magnetization

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All-optical reversible switching of local magnetization

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The authors demonstrate all-optical reversible switching of the magnetization direction in a uniformly magnetized ferrite-garnet film. The magnetization is switched by locally heating the film with a pulsed laser beam. The direction to which the magnetization flips is controlled by two parameters, the beam diameter and the pulse energy, and not by the direction of the external magnetic field. In the experiments, neither the magnitude nor the direction of the external magnetic field is changed. The results of this work illustrate the richness of optical methods to locally control the properties of magnetic materials and suggest all-optical device applications. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2760163]

Magnetic garnets have found widespread applications in science and technology due to their unique properties. They are ferrimagnetic insulators that are transparent within a broad spectral range and exhibit large Faraday rotation.[1–4] Applications of these materials include magnetic memory devices, modulators, isolators, switches, displays, and sensors.[3–13] The properties of magnetic garnets crucially depend on their composition. Bismuth-substituted ferrite garnets (FGs), used in this work, are characterized by significantly enhanced Faraday rotation in the visible wavelengths,[14–16] which makes a thin film of such material an excellent magnetic-field display. Films of this type have been used, e.g., to observe Abrikosov vortices and their motion in superconductors.[17,18] If a FG film is designed to have large coercivity and high saturation magnetization, magnetic-domain patterns recorded on the film can be used as miniature optically transparent permanent magnets, e.g., in the manipulation of magnetic colloidal particles[19–21] and trapping of dilute gaseous samples of laser-cooled atoms.[22–24] In the past few years, research attention has also been paid to ultrafast magnetization phenomena in FG materials. By employing a FG film that has in-plane magnetization and essentially no domain activity, all-optical modulation of the direction of magnetization on the femtosecond time scale has been demonstrated.[12,13]

In this work we focus on reversible optical switching between two stable magnetization states of a FG film. To maximize the Faraday effect for light transmitted through the film, we use FG films with the preferred direction of magnetization normal to the surface. We show that with laser control alone the magnetization can be switched between up and down states within a localized area of the uniformly magnetized film. The films have been grown on a (111) oriented gadolinium-gallium-garnet substrate using the liquid-phase epitaxy method. The film material is $(BiYTmGd)_3(FeGa)_5O_{12}$. The nearly square magnetic hysteresis loops of our ~ 1 μm thick films are characterized by a saturation magnetization of ~ 20 mT and a coercivity higher than 10 mT. The Faraday rotation coefficient for the films is $\theta_{FR} \approx 4.5$ deg/μm at the 532 nm wavelength used in the present experiments.

The switching of the magnetization direction in the films was studied by using the experimental setup shown in Fig. 1. An inverted microscope is incorporated in the system to obtain polarization images of the recorded domain patterns. A uniformly magnetized film is placed on the sample holder of the microscope and illuminated from above with linearly polarized light. The light passes through the film and undergoes Faraday rotation that depends on the direction of magnetization in the film. On the way to the imaging charge-coupled derice (CCD) array, the light is let through a polarizer. Thus the sign of the Faraday rotation in the film and, consequently, the domain patterns become visible. A small permanent magnet (ring shaped, with inner and outer diameters of 5 and 11 mm, respectively, and a thickness of 2.5 mm) is fixed at a height of 9 mm above the film to produce a constant bias

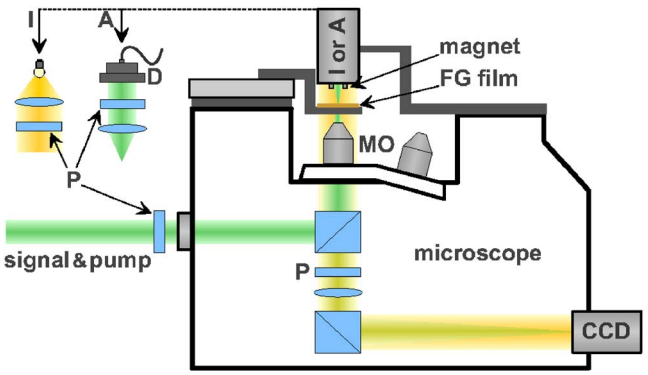

FIG. 1. (Color online) Experimental setup incorporating an inverted microscope. A FG film is placed on the sample holder in the focal plane of a 10× microscope objective (MO). Two copropagating laser beams, signal (cw) and pump (pulsed), are linearly polarized and focused with the MO. The box labeled with "I or A" stands either for an illumination system (I) or for a polarization analyzer (A). In the analyzer, the transmitted signal beam is collimated, passed through a polarizer (P), and directed to a photodetector (D). Polarization images of the domain-patterned FG film are taken with a CCD camera.

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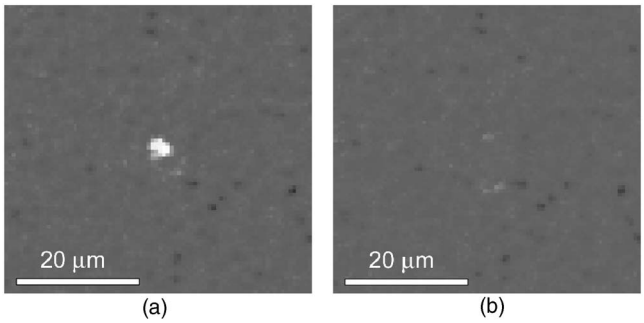

FIG. 2. All-optical recording and erasing of a microscopic domain pattern in a uniformly magnetized FG film. The pattern (a) is visible due to the opposite Faraday rotation of the illuminating light in the magnetization-flipped area; (b) shows the result of erasing of this pattern.

magnetic field of several millitesla in the direction of the initial magnetization of the film.

To reverse the magnetization, the film is heated with a 1 μs pulse of a tightly focused laser beam (pump in Fig. 1; $\lambda=532$ nm). The pump pulses, being produced by acousto-optically switching a continuous-wave laser beam, have a nearly flattop temporal profile. On the film surface, the pump beam had a peak power of 50 mW and a diameter of 3 μm. After the heating, the film cools down and the magnetization reverses in the direction opposite to that of the applied field. A typical polarization image of the resulting domain pattern is shown in Fig. 2(a). The magnetization can be flipped back by heating the magnetic-domain patterned region of the film with a different pump pulse. The pump-beam diameter in this case is set to 15 μm and the peak power is increased to 110 mW. To provide enough thermal energy the pump pulse duration is extended to 20 μs. The result of this heating is shown in Fig. 2(b), where the domain pattern recorded has disappeared. The same area of the film could be recorded and erased multiple times with no degradation of the sharpness of the recorded polarization images.

A qualitative description of the observed reversible switching of magnetization in the film can be given on the basis of the theory for thermomagnetic writing (see Ref. 25). In order to flip locally the magnetization in an initially uniformly magnetized FG film, the temperature is for a short time increased above the Curie temperature, T_C, within a small area of the film by illuminating it with a tightly focused laser beam. The ensuing temperature profile is schematically shown in Fig. 3(a) by the red dotted curve. The external magnetic field, H_e, has the same direction as the initial magnetization [$H_e<0$, as shown in Fig. 3(c)]. If the beam diameter is small, the temperature gradient at points where $T=T_C$ attains a high value. These points lie on a circle with radius r_{C1}, the so-called Curie radius. Due to the high temperature gradient, the region between the fully magnetized and fully demagnetized areas of the film is a thin ring around the focal spot [see Fig. 3(b)]. The rapid increase of the magnetization in the vicinity of the Curie radius results in a high demagnetizing field, $H_d(r)$, at $r=r_{C1}$. This field points to the positive direction and its strength slowly decreases towards $r=0$, as shown in Fig. 3(c). If the external magnetic field is such that the total field $H_t(r)=H_d(r)+H_e$ is positive at all $r<r_{C1}$, as shown in Fig. 3(d) by the red dotted curve, then, after the laser beam is switched off, the magnetization flips in the whole laser-heated area.

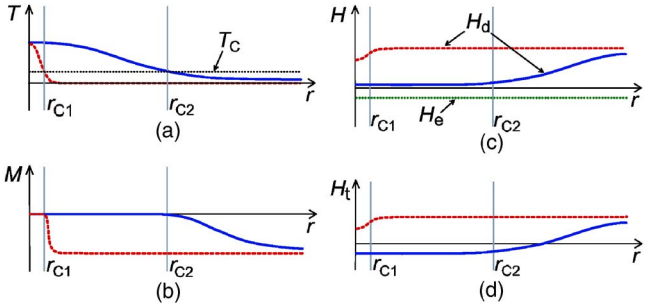

FIG. 3. (Color online) Schematic presentation of radial profiles of (a) temperature T, (b) magnetization M, (c) demagnetizing magnetic field H_d and external field H_e, and (d) total magnetic field H_t in the laser-heated film. The red dotted curves correspond to the case of tightly focused laser beam used to reverse the magnetization; r_{C1} is the Curie radius. Profiles due to heating the film with a loosely focused beam are shown with blue solid curves; the Curie radius in this case is r_{C2}.

To return the flipped magnetization back to the original direction, the film is heated with another, sufficiently wide, laser beam. The beam power (or, in the case of a short laser pulse, the pulse energy) is chosen such that the temperature rises above T_C in a large area within the laser spot. The temperature gradient near $r=r_{C2}$ is now small [see the blue solid curve in Fig. 3(a)], and the transition ring separating the demagnetized area from the fully magnetized rest of the film is thick, as shown in Fig. 3(b). The demagnetizing magnetic field is thus ensured to be weaker than the external field at all $r<r_{C2}$ [see Fig. 3(c)] so that $H_t(r)=H_d(r)+H_e$ is negative within the Curie circle [see Fig. 3(d)]. When the laser light is switched off, the initially wide temperature profile spreads further. The demagnetizing field remains weak, and the film becomes magnetized everywhere in the direction of the constant external magnetic field, i.e., in the original direction of the magnetization.

To observe the magnetization switching dynamics, we replaced the illumination system used to visualize the domain patterns with a polarization analyzer labeled by A in

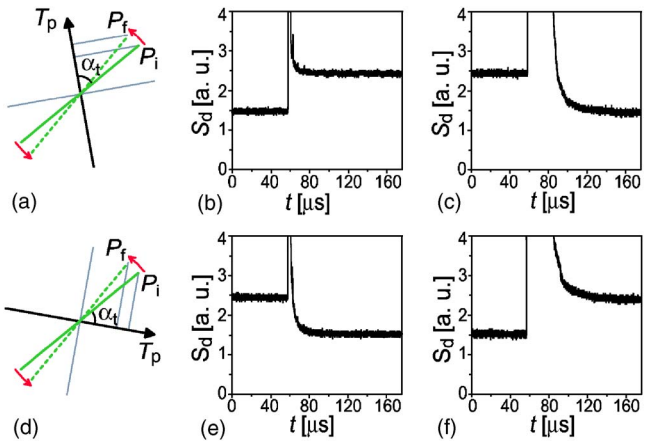

FIG. 4. (Color online) Switching between two polarization states of a linearly polarized (signal) beam passed through the film. For uniformly magnetized film, the plane of polarization of the beam at the detector (D in Fig. 1) is P_i. T_p is the transmission axis of the polarizer. When the magnetization is flipped, the Faraday rotation is reversed and the polarization plane becomes P_f. Figure (b)[(e)] shows the signal at the detector when the magnetization is flipped and the polarization plane rotates with respect to T_p as in (a)[(d)]; (c)[(f)] shows the signal when the magnetization is flipped back.

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Fig. 1. As a probe we used a weak linearly polarized laser beam (signal in Fig. 1) that is made to copropagate with the pump beam. This signal beam has a power of a few milliwatts so that its influence on the magnetization is negligible. The analyzer consists of a lens (to collimate the signal beam), a polarizer, and a photodetector. When the film is uniformly magnetized, the transmission axis of the polarizer, T_p, is tilted with respect to the polarization plane of the signal beam, P_i, by an angle α_t, as illustrated in Fig. 4(a). The signal at the detector (S_d) is proportional to $\cos^2 \alpha_t$. The initial value of α_t is set to 75°. Then, we reverse the magnetization by letting a pump pulse through the film. As a result, the polarization plane of the signal beam rotates, from P_i to P_f [see Fig. 4(a)], and since α_t becomes smaller, the signal at the photodetector increases. Figure 4(b) shows the temporal profile of the signal monitored within a time window that contains the magnetization reversal. The pump pulse is seen in the measured profile as well. When the pump power drops to zero the signal is observed to stay at a 70% higher level. Reversing the magnetization of the flipped pattern with another, erasing pump pulse returns the signal to its initial level, as seen in Fig. 4(c). We have also measured the temporal profile of the signal after rotating the polarizer to the position depicted in Fig. 4(d). In this case, Faraday rotation due to the local magnetization reversal results in a decrease of the signal, as seen in Fig. 4(e). Switching the signal to the original level by a subsequent, erasing laser pulse is shown in Fig. 4(f).

In conclusion, reversible optical switching of the direction of magnetization in an epitaxial ferrite-garnet film has been demonstrated. The switching was accomplished by locally heating the film with a pulsed laser beam of appropriate diameter and pulse energy. Since neither voltage nor electric current are needed, the switching can be used to create optical or magnetic devices that can operate under conditions where the use of electricity is undesirable. In the future, we are going to investigate optical switching of magnetization in thicker FG samples to achieve larger Faraday rotation angles and to use longer wavelengths for the signal to reduce optical absorption.

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