Light-induced Thermomagnetic Recording of Ferromagnetic Thin-film on Silicon Waveguide for Solid-State Magneto-Optical Memory

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Abstract: We firstly demonstrate light-induced thermomagnetic recording of a ferromagnetic thin-film CoFeB placed on a silicon waveguide. The magnetization reversal is observed when light propagates in the waveguide and evanescently heats up the thin-film magnet.

OCIS codes: (210.3810) Magneto-optic systems; (210.4770) Optical recording; (230.7370) Waveguides

1. Introduction

Silicon (Si) photonics is a very promising platform for high-speed and low-power photonic integrated circuits. Most of optical components such as photodetectors and optical modulators are already realized, and lasers can be integrated on Si using heterogeneous integration techniques. As applications of the magneto-optical (MO) devices on photonic integrated circuits, the optical isolator, the optical circulator, and the optical switch have already been reported [1-4]. All of them are controlled by an external magnetic field, and the magnetization reversal controlled by light propagating in the waveguide has not been reported so far.

The MO recording was a traditional recording scheme for the data storage on personal computers, which utilizes thermomagnetic recording and MO readout techniques [5]. However, nowadays, MO drives had been replaced by hard-disk drive or other optical storage media such as compact discs and digital versatile discs because of the complex system combining optical data-storage techniques and magnetic storage media for the MO recording.

In this paper, for the first time, we demonstrate light-induced thermomagnetic recording of a thin-film magnet CoFeB on a Si photonics platform. The coercive force of the magnetic film placed on the Si waveguide is controlled by heating due to the absorption of lightwave propagating in the waveguide. Therefore, by applying a magnetic field, the magnetization reversal occurs. The proposed scheme can be applied to a solid-state waveguide MO memory in which neither free-space optics nor mechanical rotation system is needed.

2. Device design and fabrication

At first, we measured the in-plane magnetic property of the ferromagnetic thin-film CoFeB using superconducting quantum interference device (SQUID) at different temperatures of 300 K, 350 K and 400K. A 40-nm-thick CoFeB film was grown on a Si/SiO_2 substrate deposited with a 10-nm-thick Ru underlayer. As shown in Fig 1, the coercive force H_c was decreased by ~17 Oe when temperature was raised by 100 K from 300 K to 400 K.

For testing the thermomagnetic recording on the Si waveguide, we designed CoFeB film with a footprint of 5 µm × 15 µm on a SiO_2 clad of Si waveguide to observe the magnetic domain of CoFeB using the magneto-optical Kerr effect (MOKE)

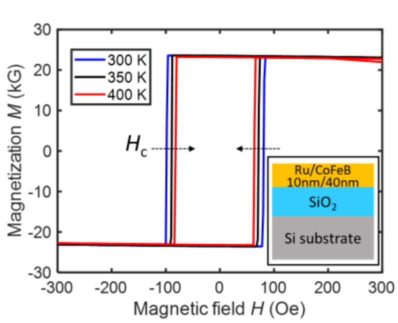

Fig. 1. In-plane magnetic property of CoFeB measured using SQUID. The inset shows the structure of the measured sample.

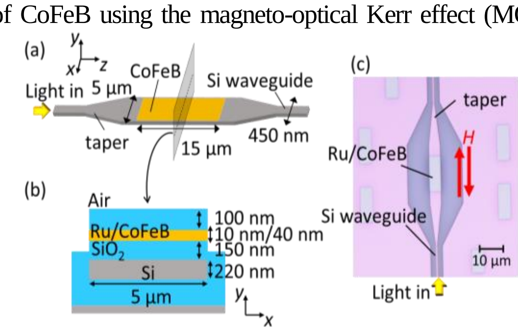

Fig. 2. Images of the thin-film magnet loaded on Si waveguide for testing photothermal magnetic recording. Schematic image of (a) 3D perspective view, and (b) 2D cross-sectional view along the dot line in (a), and (c) microscopic image of the fabricate device.

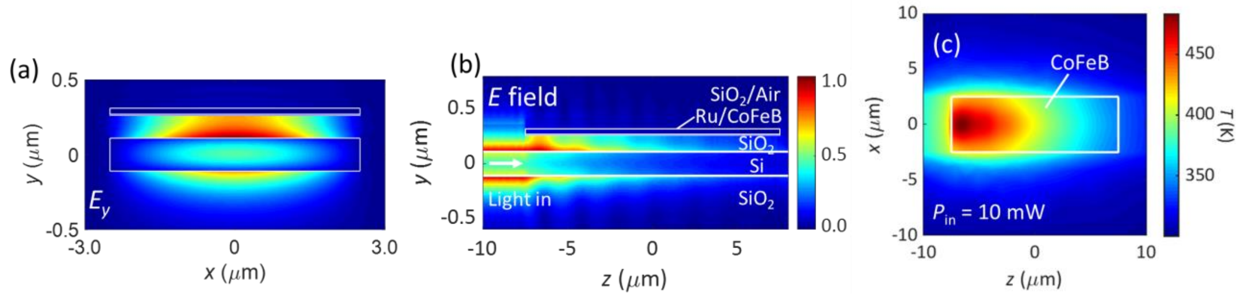

Fig. 3. (a) 2D cross-sectional profile for E_y of TM mode simulated by FEM, and (b) E field distribution of light guiding in the waveguide simulated by FDTD method. (c) Simulated temperature increase due to optical absorption of CoFeB for a 10-mW CW light input to the waveguide

microscope. The schematics of the perspective and cross-sectional views of the sample are shown in Figs. 2(a) and (b), respectively. By forming the rectangular shape of the CoFeB film, its magnetization is easily aligned along the longer side due to the magnetic shape anisotropy. The width of the 450-nm-wide Si waveguide is extended to 5 μm using taper waveguides. We simulated both the light propagation and light-induced heating. As a polarization of light source, the more absorptive fundamental transverse magnetic (TM) mode at a wavelength of 1550 nm is used. In Fig. 3 (a), the cross-sectional mode profile of the fundamental TM mode is shown. From the result, the absorption loss due to evanescent coupling to CoFeB is calculated to be ~1 dB/μm. Figure 3 (b) shows the electric field distribution of TM-mode light travelling along z axis in the Si waveguide with the magnetic film simulated by a finite-difference time-domain (FDTD) method. The guiding light evanescently couples to the CoFeB film and the launched optical power is absorbed by the film. Subsequently, the absorbed optical energy generates heat within the CoFeB film, increasing its temperature [6]. In order to analyze such photothermal effect, a 3D heat transport is simulated based on the finite element method (FEM). The steady-state temperature distribution of the surface of the CoFeB film is shown in Fig. 3 (c). Since the optical power is attenuated due to the absorption of Ru/CoFeB along the propagation direction, the heat generated within the magnetic film is not uniform. Temperature of the CoFeB layer becomes highest at the side edge of the film coupled with light. The maximum increase in temperature is ~180 K for a 10-mW CW light input, which sufficiently reduces the coercive force of the CoFeB film.

3. Experimental results

We investigated a thermal effect to the magnetic property induced by the optical absorption. The microscopic image of the fabricated CoFeB film placed on a Si waveguide is shown in Fig. 2 (c). The optical power-dependent magnetic property of CoFeB was measured using an MOKE microscope equipped with a 50× objective lens. The device under test was set on a stage with an electromagnetic coil, which applied a magnetic field in the in-plane along the longer side of the CoFeB film at room temperature. Linearly polarized-light was illuminated onto the sample. The MOKE microscope collected the light reflected by the sample, and the image of magnetic domains of CoFeB was obtained by analyzing the difference in the brightness of the measured image from the reference image due to the MO Kerr rotation. The TM polarized light from the tunable laser diode at a wavelength of 1550 nm was launched into the device though a cleaved facet of the waveguide. The optical power was varied from 1 to 12.5 mW. The measured magnetic property of CoFeB for different optical powers is shown in the Fig. 4 (a). The measured magnetization is normalized by the residual magnetization. The coercive force is changed depending on optical powers

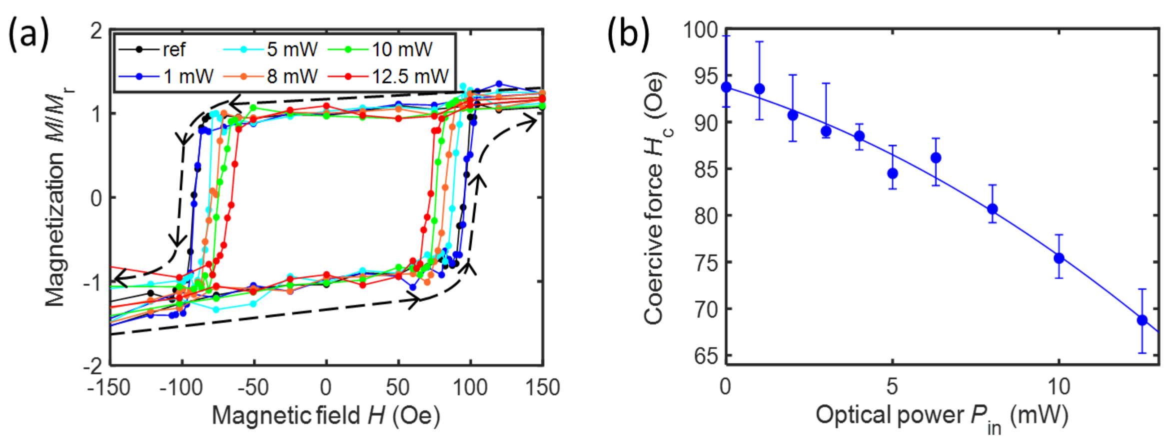

Fig. 4. Experimental results of optical power dependent magnetic properties of the CoFeB film on the Si waveguide measured using the MOKE microscope. (a) Hysteresis loops of relative magnetization direction, and (b) coercive force H_c for different optical powers.

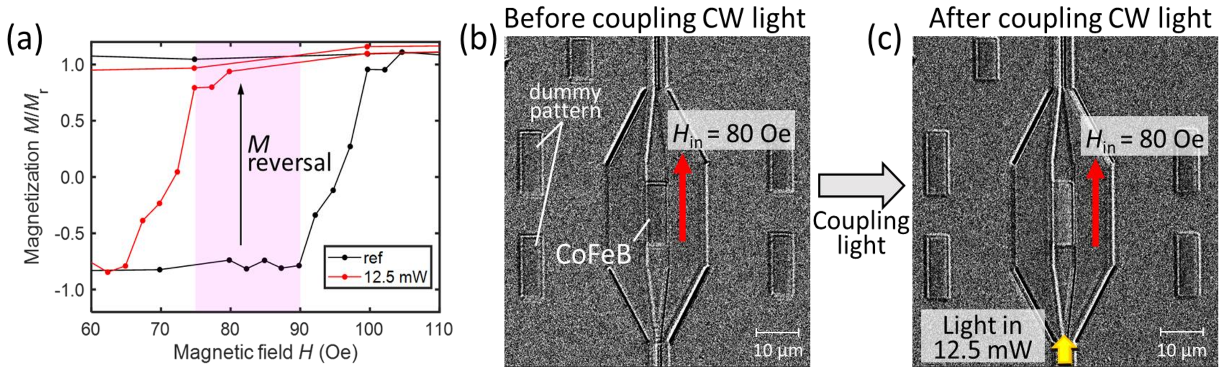

Fig. 5. Experimental demonstration of the thermomagnetic recording. (a) Applied external magnetic field for photothermal magnetization reversal determined by the hysteresis loops for input optical powers of zero and 12.5 mW. (b) and (c) show magnetization directions of CoFeB on the Si waveguide observed by MOKE microscope before and after coupling a 12.5-mW CW light to the waveguide, respectively.

as shown in Fig. 4 (b). As the optical power is increased, the coercive force is decreased because the temperature of the CoFeB film is raised due to the optical absorption as discussed in Section 2.

We experimentally demonstrate the thermomagnetic recording of the thin-film magnet on the Si waveguide. Figure 5 (a) shows the magnetic property of the CoFeB film taken from Fig. 4 (a) for optical powers of zero and 12.5 mW. When coercive force is reduced by light-induced heating, magnetization reversal occurs by applying a magnetic field of 75 - 90 Oe. In this study, a constant magnetic field of ~80 Oe was applied. In the initial state before coupling light to the waveguide, magnetizations of the CoFeB film on and outside the waveguide are identical as shown in Fig. 5 (b). Subsequently, CW light of 12.5 mW is launched into the waveguide, which results in the change in magnetization only on the waveguide as shown in Fig. 5 (c). This represents the thermomagnetic recording induced by light propagating in the Si waveguide. The highest temperature of the CoFeB is estimated to be ~530 K by the simulation. The light-induced magnetization reversal was also achieved using a modulated rectangle light pulse. When 50 ns light pulses with a 50-mW peak power was coupling to the Si waveguide instead of CW light, the similar change of the contrast of the magnetic domain of CoFeB was observed. By reducing the volume of the CoFeB film, the required optical power for the magnetization reversal can be reduced.

4. Conclusions

We demonstrate for the first time light-induced thermomagnetic recording of the ferromagnetic thin-film magnet CoFeB placed on the Si waveguide. The coercive force of the thin-film magnet was reduced by heating due to the optical absorption of travelling light evanescently coupled from the waveguide. When a magnetic field of ~80 Oe was applied, the magnetization reversal occurred with 12.5-mW CW light launched into the waveguide. A compact solid-state MO recording system can be realized on the Si photonics platform by utilizing the proposed scheme. The MO readout can be achieved by employing an MO phase shift to a Mach-Zehnder interferometer or a microring resonator [7].

Acknowledgments

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