Development of a high-speed and a high-sensitive laser scanning magneto-optical imaging system

H. Murakami, R. Kitamura, I. Kawayama, M. Tonouchi
Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: hiro@ile.osaka-u.ac.jp

Abstract. A high-speed and a high-sensitive laser scanning magneto-optical (MO) imaging system have been developed. In the high-speed imaging mode, we have succeeded in almost the real time observation of MO images with the sensitivity better than 100 μT. On the other hand, in the high-sensitive mode using an acoustic-optic modulator and a RF lock-in amplifier, it was found that the system noise reduced into the magnetic field strength was less than 6 μT at the data acquisition time of 10 μs. In this mode we have also succeeded in the fast MO imaging of the magnetic flux penetration into a square-shaped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film at ~0.3 s/frame for 128x128 and ~5 s/frame for 500x500 pixels’ image.

1. Introduction
Developments of superconductor devices utilizing magnetic flux quanta, such as a single flux quantum logic circuit, a superconductive quantum-bit device, an optical magnetic flux device, etc. have attracted much attention as candidates for the next-generation operational device, in addition to its low power consumption. [1-4] In the development of such devices, direct evaluation of the magnetic flux states in its driving mode would be very useful to improve the device performance. In the detection of the quantum states of the magnetic flux in a superconducting device, magneto-optical (MO) microscope is one of useful tools for its high spatial resolution, a high speed measurement, and a quantitative evaluation of magnetic flux. [5] However, the sensitivity of conventional MO microscope with a cross-nicol polarizer is at most several mT. Therefore, to obtain a fine image with a high sensitivity much better than 1 mT, we have to observe a large amount of images for the data processing such as multiplication, subtraction, and averaging. To improve the sensitivity in the MO microscope and directly obtain the local MO signal as an optical or electrical signal, we have developed a laser scanning MO imaging system which enables us to carry out a high-speed and a high-sensitive measurement with the sensitivity better than 10 μT.

2. Laser scanning magneto-optical imaging system
Figure 1 shows an optical diagram of the fabricated laser scanning MO imaging system. It is equipped with an argon multiple line laser (40 mW@514 nm & 40 mW@488 nm) and a laser diode module (20 mW@630 nm) as an optical sources. In the present study a green laser with a wavelength of 514 nm is used as the light source.
In this system, the laser beam which is linearly polarized by a polarizer is focused on the sample surface by using an objective lens (Mitsutoyo MPlan APO x20 or x50). To obtain a two-dimensional MO image, the focused laser beam is scanned over the sample surface by using a set of galvano meters. The laser beam reflected from the sample surface is collimated into an optical fiber with a core diameter of 100 μmφ by using a spatial filter after being transmitted through an analyzer. To detect the MO signal, the polarization plane is set to be almost perpendicular to that of the polarizer, and finally detected by using a photomultiplier (PM) [H6780: Hamamatsu Photonics K.K.].

In a high speed mode, we don’t use the acoustic-optic modulator (AOM) or RF lock-in amplifier (see Fig.1a). In this case, the maximum power of the incident laser beam into the sample is about 4 mW and the output current signal from PM is further amplified by using a high-frequency amplifier. Here, the gain of the PM is larger than 10^5 A/W, and that of the amplifier can be increased up to 10^7 V/A. To obtain MO images, Sampling of pixel data is directly carried out by using an AD input board (Interface PCI-3163: maximum sampling speed 0.1 μs/S) without any multiplication or averaging process. Therefore, it is possible to carry out almost the real time MO imaging in this mode.

In a high sensitive mode using a RF lock-in amplifier, the laser beam emitted from the laser source is optically modulated by the AOM at 500 kHz, and the modulated MO signal from PM is detected by using the RF lock-in amplifier. In the observation of MO images, the pixel data are obtained at the time interval corresponding to the time constant value of the lock-in amplifier (minimum time constant: 10 μs). In this setup, the system sensitivity is independent of the imaging speed. Therefore, if the spatial resolution is disregarded, we can do the fast-imaging at 0.3 s/frame for 128x128 pixels or ~5 s/frame for 500x500 pixels at the data acquisition time of 10 μs.

3. Faraday indicator

It is important to optimize the Faraday indicator, because the spatial resolution and the signal intensity

Figure 1. Optical diagram of the fabricated magneto-optical imaging system. The acoustic optic modulator (AOM) and a RF lock-in amplifier (BW:200 MHz) are used in a high-sensitive imaging mode. The maximum gain and BW of the pre-amplifier are 10^7 V/A and 350 MHz, respectively.

Figure 2. (a) A photograph of a YBCO SVFT device, (b) a laser reflection image of the bridge region of the SVFT device, and (c) a line scan profile along the inserted line of (b). It can be seen that the spatial resolution better than 500 nm is realized in the fabricated system.
strongly depend on its thickness. In fact, the Faraday rotation angle increases with increasing the thickness, while the power of the laser transmitting through the indicator decreases with increasing the thickness due to absorption. As for the Faraday indicator, bismuth substituted rare earth iron garnet has a large Faraday rotation angle at 514 nm. Therefore, we prepared its polycrystalline films on MgO (100) single crystal substrates by means of the metal organic decomposition (MOD) method, because the film thickness can be easily controlled by number of spin-coating process. In the present study, we prepared the MOD garnet film of ~1.4 μm-thick (36 times-spin coating). The MOD garnet film covered with Al reflection layer was tightly put onto the sample surface by using ball plungers, and a set of the sample was mounted on the sample holder in a pulsed tube refrigerator without any magnetic shields.

4. Experimental results and discussions

We have carried out primitive observations to evaluate the system performance. Firstly, we evaluated the spatial resolution as a laser microscope. Figures 2a and 2b show a photograph and a laser reflection image (corresponding to 500x500 pixels) of the bridge region of an YBa$_2$Cu$_3$O$_{7-δ}$ (YBCO) superconductor vortex flow transistor (SVFT) device, respectively. Figure 3c shows a line scan profile along the inserted line of Fig. 2c. As shown in Fig.2c, we obtained the spatial resolution better than 500 nm as a laser microscope. Therefore, if we use a single crystal garnet film as a Faraday indicator, it will be also possible to obtain a MO image with almost the same spatial resolution.

To check the magnetic sensitivity in the high-speed imaging mode, we observed the local MO signal inside the loop of the SVFT device. Figure 3 shows the local MO signal observed under a control current condition of 200 mA@1 kHz. In this device, since the loop size is 10x8 μm$^2$, the corresponding magnetic field to a single magnetic flux quantum ($Φ_0=2.07\times10^{-7}$ gauss·cm$^2$) generated inside the loop is about 26 μT. Therefore, the intensity of the MO signal, ~100 μT, corresponds to 4$Φ_0$. Since the critical supercurrent of the bridge line is as high as about 100 mA, a small number of magnetic flux quanta could enter into and exit the loop even if such a large control current was applied to generate the magnetic flux due to the Meissner effect by the superconducting loop. This result also shows that the noise level of the high-speed imaging mode is about 70 μT. To reduce the noise level in the high-speed imaging mode, equipment of magnetic shield around the sample holder may be effective.

On the other hand, Figs. 4a and 4b show the high-speed MO images of the SVFT device observed under magnetic field of 54 mT applied perpendicular to the sample and after removing the magnetic field, respectively. Here, the brightness corresponds to the magnetic flux density. It can be seen in Fig. 4a that the magnetic fluxes mainly penetrate into the space region between the YBCO lines due to the Meissner effect. On the other hand, it can be seen that the magnetic fluxes are trapped at the edge.
regions of YBCO after removing the external magnetic field in Fig 4b. In these measurements, we confirmed that the quality of MO image is almost independent of the laser scanning speed. We also checked the system noise level in high-sensitive mode. Fig.5 shows the MO signal of the garnet film in the perpendicular magnetic field with the amplitude of \( \sim 50 \) \( \mu \)T at 100 Hz. The measurement was carried out under the time constant condition of the RF lock-in amplifier at 10 \( \mu \)s. It can be seen in the inset that the system noise level is as low as \( \sim 6 \) \( \mu \)T. As for this noise level, we can easily reduce it by increasing the time constant value, if the imaging-speed is disregarded.

Using this system MO imaging was also carried out on a square-shaped YBCO thin film under perpendicular magnetic field at the acquisition time for the pixel data of 10 \( \mu \)s. Figures 6a and 6b show the observed MO images. Here, the brightness corresponds to the magnetic flux density. When the applied magnetic field was 4.5 mT, the magnetic fluxes penetrated only the edge regions of the sample, as shown in Fig. 6a. Increasing the magnetic field, the magnetic fluxes symmetrically penetrated inside the superconductor from every side. Furthermore, flux free areas remained in the central part and along the diagonals, as shown in Fig. 6b. This characteristic magnetic flux penetration shows a good agreement with the previous data. [6]

5. Summary
We have fabricated a scanning laser MO imaging system of high-speed and high-sensitive mode. The fabricated system shows a spatial resolution less 500 nm as a laser microscope. We have succeeded in the observation of almost real time MO image by using the high-speed imaging system, and also succeeded in the reduction of the system noise level below 6 \( \mu \)T in the high-sensitive imaging system.

Acknowledgment
This work was supported in part by a Grant-in-Aid for Scientific Research (B) No. 20360159 from the JSPS.

References
[1] Likharev K K and Semenov V K 1991 IEEE Trans. Appl. Supercond. 1 3
[2] Inomata K, Sato S, Nakajima K, Tanaka A, Takano Y, Wang H B, Nagao M, Hatano H and Kawabata S 2005 Phys. Rev. Lett. 95 107005
[3] Tonouchi M, Wada M, Hangyo M, Tani M and Sakai K 1997 Appl. Phys. Lett. 71 2364
[4] Doda Y, Kawayama I, Murakami H and Tonouchi M 2006 IEICE Trans. Electron. 88C 177
[5] Johansen T H, Bazilierich M, Braistsberg H, Galperin Y, Lindelof P E, Shen Y and Vase P 1996 Phys. Rev. B 54 16264
[6] Jooss Ch, Albrecht J, Kuhn H, Leonhardt S and Kronmuller H 2002 Rep. Prog. Phys. 65 651