AIP Journal of Applied Physics

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S. J. Lee, Y. Melikhov, D. C. Jiles, C. M. Park, and H. Hauser

Citation: J. Appl. Phys. 99, 08B301 (2006); doi: 10.1063/1.2159390
View online: http://dx.doi.org/10.1063/1.2159390
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v99/i8
Published by the American Institute of Physics.

Magneto-optic linear-displacement sensor with high spatial resolution and low noise

S. J. Lee,[a)] Y. Melikhov, and D. C. Jiles
Center for Nondestructive Evaluation, Iowa State University, Ames, Iowa 50011

C. M. Park
Department of Physics, Seonam University, Namwon 590-711, Korea

H. Hauser
Institute of Sensor and Actuator Systems, Vienna University of Technology, A-1040 Vienna, Austria

(Presented on 1 November 2005; published online 17 April 2006)

A magneto-optic linear-displacement (MOLD) sensor is reported for measuring linear displacements of the surfaces of materials remotely. It is based on observation of temporal changes in the intensity of the reflected polarized light beam, which passes through a magneto-optic thin garnet film with controlled periodical displacement of one domain wall. The MOLD sensor allows observation of linear displacement of a material located remotely from the laser and detector with a spatial resolution of 4 μm. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2159390]

I. INTRODUCTION

As automation increases, so does the demand for a development of sensors. Optical sensors have advantages over other type of sensors in that they can provide noncontact operation, greater sensitivity, freedom from electromagnetic interference, wide frequency, and dynamic ranges. From these advantages, optical techniques may be ideal for the development of sensors for the measurement of material thickness and mechanical deformation under external stress and as a feedback sensor for dynamic control applications. These are important topics in materials processing.

In optical sensor techniques, light receivers such as charge-coupling devices (CCDs) or position-sensitive detectors (PSD) are among the core elements in the sensor systems. Optical sensors employing CCDs have a limitation of resolution defined by the pixel size, which is at best about 5 μm.[1] The PSD technique allows continuous tracking of the position of the light spot so that it can be used in an optical sensor for noncontact distance measurement, but the reproducibility of the measurements is rather poor.[2] Moreover, the PSD technique is not suitable as a linear-displacement (LD) sensor for measuring an object moving perpendicular to the surface of a plane on a submicrometer scale.[2]

In this work, a magneto-optical (MO) method for the measurement of linear displacement is presented. The principle of this method is based on modulation of Faraday rotation due to domain-wall motion in a magneto-optic sensor film under the influence of ac and dc magnetic fields. The domain-wall motion in a MO film has been utilized before for the development of a variety of sensors: a magneto-optic sensor measuring the light-beam positions by means of the magneto-optical spatial light modulation in a plate of yttrium orthoferrite,[3] a magneto-optical rotational speed sensor measuring angular velocities using the domain-wall motion in an orthoferrite plate,[4] and a magneto-optic switch based on the domain-wall motion in yttrium orthoferrite crystals.[5] In a previous paper, we have reported a utilization of domain-wall motion as a sensor for evaluation of surface deformation.[6] The surface deformation was simulated by mounting an aluminum mirror on a rotator providing pure rotational motion, with a sinusoidal ac drive field applied to the surface of the MO film. In this paper, we studied a magneto-optic sensor system for sensing pure linear displacements of an object moving perpendicular to the surface of a plane. In order to achieve this, we changed the configuration of the magneto-optic sensor system and system parameters to optimize the system to work as a linear-displacement sensor. We proved successfully that this system works as a linear-displacement sensor. In this study, we found that the performance of the present sensor system is largely independent of the intensity of reflected light and therefore can be used on a variety of different surfaces with different reflectivities.

II. EXPERIMENTAL DETAILS OF THE SENSOR

To test the response of the magneto-optic linear-displacement (MOLD) sensor we used a He–Ne laser, an analyzer, and a photodetector which were located 1 m away from a mirror, which was used as a test sample. We used a MO garnet film which is a bismuth-doped iron garnet $(Bi,Tm)_3(Fe,Ga)_5O_{12}$ (with a thickness ∼3 μm) grown on a thin substrate of gadolinium gallium garnet (GGG) (with a thickness of 0.5 mm). The bismuth-doped iron garnet film has a large specific Faraday rotation θ_F, up to 2.3°/μm of thickness. The domain walls in the bismuth-doped garnet MO film with thickness of 3 μm are activated at a threshold magnetic field of 0.1–0.3 mT.

Two hard ferrite magnets (remanence B_R=0.350 T and coercivity H_C=260 kA/m) with opposite polarities were arranged near the MO film to create a two-domain structure with up and down magnetizations and a domain wall between them. When the up domain covered both the incident

[a)]Electronic mail: sjlee@ameslab.gov

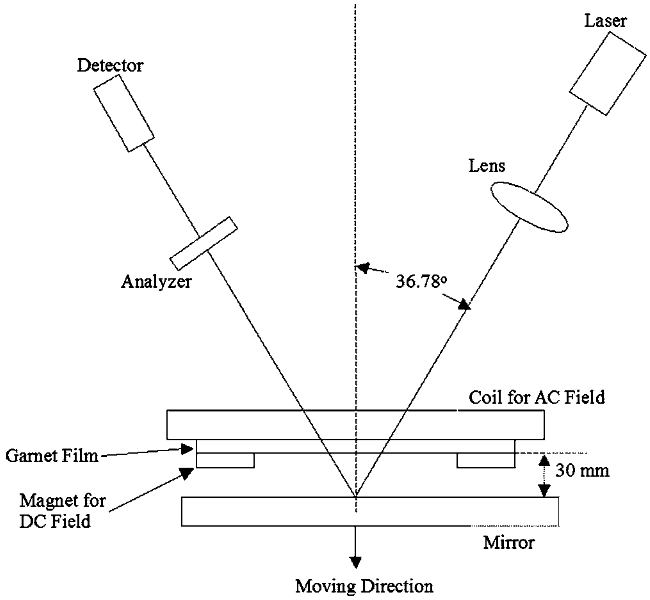

FIG. 1. Schematic diagram of the magneto-optic linear-displacement sensor.

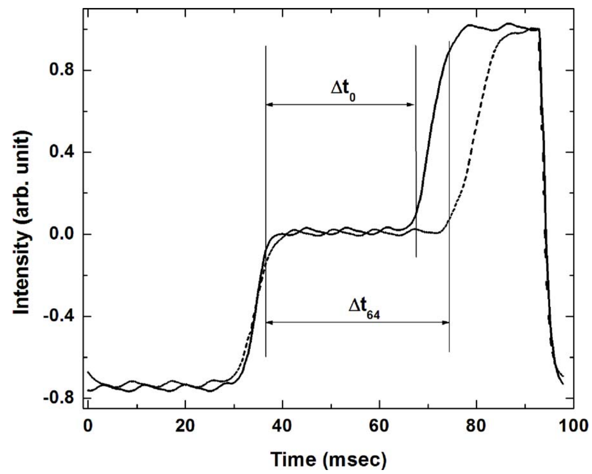

FIG. 2. Intensity of the reflected light beam vs time measured using the MOLD sensor. The solid line is the light intensity measured when the mirror was located at a reference distance (30 mm from the garnet film); the dotted line is the light intensity measured when the mirror was moved 64 μm away from the reference distance.

and reflected light-beam paths, the Faraday rotations of polarization summed up to produce a positive rotation. Conversely, when the down domain covered both light beams, then the sign of Faraday rotations was negative. Finally, when the incident and reflected light beams pass through different domains, the total Faraday rotation was zero.

The distance between the two permanent magnets was 50 mm, and the distance between the sample and the sensor was 30 mm. An ac excitation coil was located above the sensor film, as shown in Fig. 1. A sawtooth wave form with a frequency of 10 Hz was generated, which caused the domain wall between oppositely magnetized domains to oscillate.

III. RESULTS AND DISCUSSION

In order to test the response of the sensor the mirror was moved away from the garnet film in incremental steps of 16 μm. As an example, Fig. 2 shows the time dependence of the intensity of the reflected light beam at a reference distance (when the mirror was located 30 mm from the garnet film) and at a distance of 64 μm farther away from the reference distance. The temporal changes in the behavior of the intensity represent the changes in the time interval for the domain wall to move between a point where the incident laser beam hits the garnet film and a point where the reflected laser beam hits the garnet film from a mirror: Δt_0 is for reference distance and Δt_{64} is for a mirror located 64 μm farther away from the reference distance.

As the laser beam has a finite diameter and the domain wall is not infinitely thin, the transition of intensity at the points where incident and reflected laser beams hit the garnet film is not steplike but gradual with a slope, as shown in Fig. 2. Due to this finite size of the laser beam, Δt is computed between two points at which the derivative of the intensity versus time is maximum.

Figure 3 shows Δt measured at a reference distance (0 μm) and at increased distances with incremental steps of 16 μm from the reference distance. At each distance, Δt was measured ten times and the average values of Δt were recorded together with the errors. As the sample moved backward a distance of 64 μm with a step of 16 μm, we observed a linear increase of Δt as shown in Fig. 3. The smallest movement the sensor can successfully detect could be computed by knowing the error bar of Δt measurement, which is about 0.66 ms, and the average value of the slope, which is $\Delta t/\Delta x=0.162$ ms/μm, found from Fig. 3. This allows successful discrimination of sample movement by 4 μm. The resolution of the system does not depend on the applied ac excitation as long as the frequency is not high enough to disturb the response of the domain wall on ac excitation. The trend and resolution were found to be the same within the frequency region from 10 to 100 Hz. As the error bars in Fig. 3 representing the noise are much smaller than the signal—for example, at zero displacement the average value was 34.75 ms and the error bar was 0.32 ms—this can be considered to be a low-noise sensor system.

The resolution can be improved by employing a size of

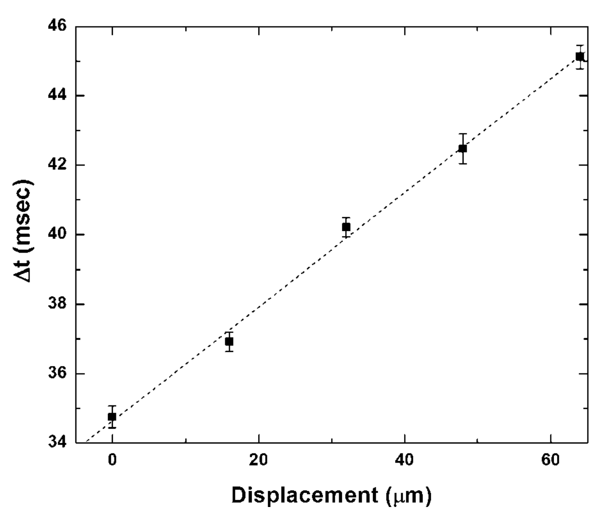

FIG. 3. Temporal changes of the intensity Δt as a function of displacement.

laser beam smaller than the current beam size which is about 1 mm diameter. Reduced beam size leads to narrower transition regions where changes from negative Faraday rotation to zero Faraday rotation and from zero Faraday rotation to positive Faraday rotation occur. As a result of narrowed transition region, we can measure Δt more accurately. We expect that we can reduce the data-taking step to 0.04 ms when beam size becomes 0.2 mm. Another way of enhancing resolution is to use a larger diameter of solenoid so that the angle of incidence becomes larger. By doing this, we can obtain larger Δt for the same movement of sample. For example, when the angle of incidence becomes 56°, then the width of Δt doubles that of the current angle of incidence which is 36.78°.

The maximum linear displacement which could be detected is restricted by the domain-wall range of movement, which in some way could be controlled by the maximum applied ac field. In this system, the maximum is achieved around 150 μm with the resolution of 4 μm.

IV. SUMMARY AND CONCLUSIONS

In this work a magneto-optic linear displacement (MOLD) sensor for remotely measuring linear displacements of the surfaces of materials has been studied experimentally. This sensor allows observation of a linear displacement of a material located far from the surface of the test material with resolution down to 4 μm.

Displacements of the surface are detected through the observation of changes in the time characteristics (Δt) of intensity. As this signal is independent of the material properties, the technique allows for the estimation of linear displacement for all types of materials: magnetic, nonmagnetic, conducting, and nonconducting materials.

ACKNOWLEDGMENT

This research was supported by the National Aeronautics and Space Administration (NASA) under Award No. NAG-1-02098.

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