Magneto-Optic Magnetic Field Sensors Based on Uniaxial Iron Garnet Films In Optical Waveguide Geometry

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Abstract—Iron garnet films which exhibit perpendicular uniaxial magnetic anisotropy are promising materials for magneto-optic magnetic field sensing. In an optical waveguide geometry, these materials exhibit large values of saturation Faraday rotation which in turn produce high sensitivity. The domain structure of these films favors magnetization rotation as the primary magnetization process. This process is significantly faster than domain wall motion, which is the primary magnetization process in bulk iron garnet crystals. We present data which confirm the high sensitivity and wideband frequency response of these materials. One film exhibits a virtually flat frequency response from dc to at least 1 GHz. Potential problems with waveguide sensors, such as birefringence and optical coupling efficiency, appear to be soluble.

I. INTRODUCTION

The ferrimagnetic iron garnets have been exploited for magnetic field sensing in both bulk and film structures. Recent experiments demonstrated the potential of garnet films in waveguide geometries in which light propagates within the plane of the film[1-3]. Films with perpendicular uniaxial magnetic anisotropy seem particularly promising since such films do not require the external biasing magnetic fields that are typically required with films which preferentially magnetize in-plane. In the demagnetized state, films with sufficient uniaxial anisotropy energy exhibit alternating domains magnetized either up or down relative to the film's surface. A magnetic field applied in the plane of such a film rotates the magnetization of both types of domains toward the applied field equally. Thus, magnetization rotation, as opposed to domain wall motion, should be the dominant response to in-plane magnetic fields in these films. For magnetic field sensing, magnetization rotation is preferred over domain wall motion since it does not generally produce hysteresis and is also typically faster than domain wall motion. Therefore, sensors exploiting these films in a waveguide geometry should exhibit a fundamentally linear response (without Barkhausen jumps) and a higher frequency response than sensors based, for example, on bulk iron garnet crystals.

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The fabrication technique and physical properties of the thick films used in this study have been described previously (Films 1 and 2 in Ref. [4]). Film 1, of the composition $(BiY)_3Fe_5O_{12}$, was 60 μm thick and, after cutting and polishing, about 2.5 mm long. Film 2, of the composition $(BiTb)_3(FeGa)_5O_{12}$, was 100 μm thick and also about 2.5 mm long. Both films were grown by liquid phase epitaxy (LPE) on Ca-Mg-Zr–substituted gadolinium gallium garnet (111)-oriented substrates.

A single-mode optical waveguide in an iron garnet film would typically require a film thickness on the order of 1 μm. The number of modes propagating in the films used in this study, therefore, is quite large. On the other hand, the general conclusions drawn from this study, regarding the fundamental response function, frequency response, and hysteresis of iron garnet films used in a waveguide geometry, should not depend on film thickness.

II. MAGNETO-OPTIC RESPONSE

The magneto-optic responses of both films were measured with the detection system shown in Fig. 1.

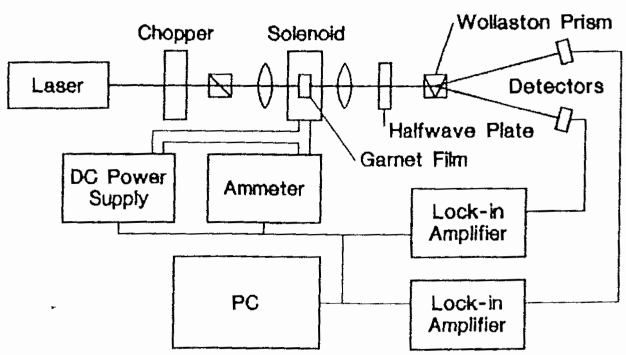

Fig. 1. System for measuring magneto-optic response.

Linearly polarized light from a diode-pumped Nd:YAG laser (λ = 1.32 μm) was focused onto the edge of the film with the axis of polarization parallel to the plane of the film. All measurements were made at room temperature. After propagating several mm through the film, the light was recollimated. A halfwave plate was employed to rotate the polarization plane of the light by 45°. The light then passed through a Wollaston polarizing beamsplitter which divided the light into its vertically and horizontally polarized components. The resultant two beams were detected separately with InGaAs detectors coupled to transimpedance amplifiers. No attempt was made to exactly match the gain of the detector amplifiers. Two lock-in amplifiers, referenced to a mechanical chopper, recorded the signals from the detectors as current was applied to a solenoid positioned around the iron garnet film.

The measured magneto-optic responses of Film 1 are shown in Fig. 2. The sinusoidal oscillations in the data

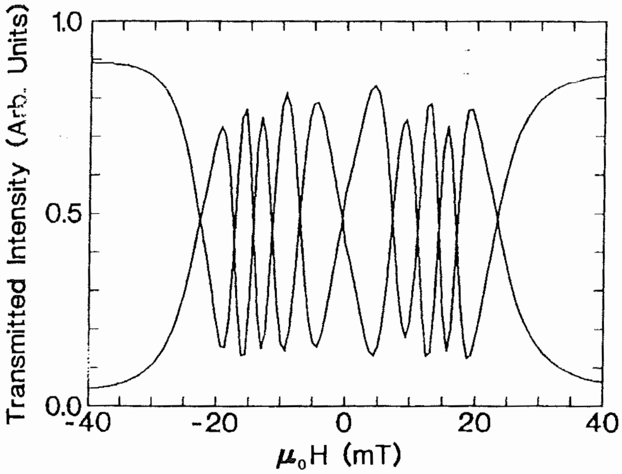

Fig. 2. Measured magneto-optic responses for Film 1.

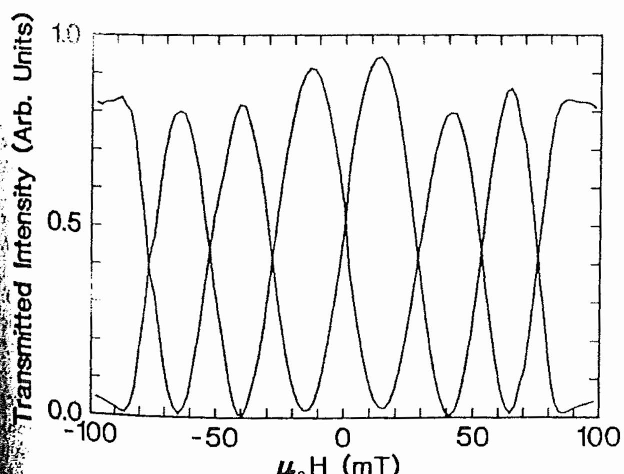

Fig. 3. Measured magneto-optic responses for Film 2.

occur as the polarization plane rotates by multiples of π rads. Two features of the data of Fig. 2 indicate nonideal behavior. First, the incremental field between adjacent peaks (and valleys) in the data is largest at small fields and smallest at fields just below the saturation field H_{sat} (~29 mT). This effect suggests a nonlinear magnetization curve. Second, the "fringe contrast," defined as the ratio of the amplitude of the intensity oscillations to the mean intensity, is significantly less than unity for $H < H_{sat}$, but approaches unity for $H > H_{sat}$. Linear birefringence, which can reduce fringe contrast [5], is not likely the cause in this case since, for $H < H_{sat}$, there is no obvious increase in fringe contrast as H increases.

As shown in Fig. 3, the measured magneto-optic response of Film 2 is much more ideal than that of Film 1. Specifically, the fringe period is much more consistent, and the fringe contrast is close to unity. On the other hand, H_{sat} for Film 2 (~120 mT) is much greater than H_{sat} for Film 1 (~29 mT), whereas the saturation Faraday rotation θ_F^{sat} of Film 2 (~330°) is much less than that of Film 1 (~500°). (The optical path length for both films was approximately 2.5 mm.) Both of these effects reduce the sensitivity ($d\theta_F/dH$) of Film 2 compared to Film 1.

III. Frequency Response

As described in Ref. [4], the domain structure of both Films 1 and 2 consists predominantly of perpendicularly magnetized domains. A magnetic field applied in the plane of such a film will generally be perpendicular to the magnetization of both up and down domains. In this geometry, the movement of domain walls can not by itself produce a net magnetization component parallel to the in-plane field. Rotation of the domains' magnetization, which results directly in an in-plane magnetization component, should thus be the dominant mechanism of magnetization in these films. The frequency response of magnetization rotation is associated with ferromagnetic resonance, which, unlike domain wall motion resonance, often occurs at frequencies in excess of 1 GHz. The frequency for ferromagnetic resonance is given by the equation

$$\omega_r = \mu_0 \gamma H_K' , \qquad (1)$$

where ω_r is the resonance frequency, γ is the gyromagnetic ratio, and H_K' is the effective anisotropy field.

Previously [4], the frequency response of these films was measured magneto-optically in a geometry which favored domain wall motion. Film 1 exhibited a resonance near 550 MHz, above which the frequency response rolled off rapidly. Film 2 exhibited no resonance and a 3 dB frequency of about 5 MHz.

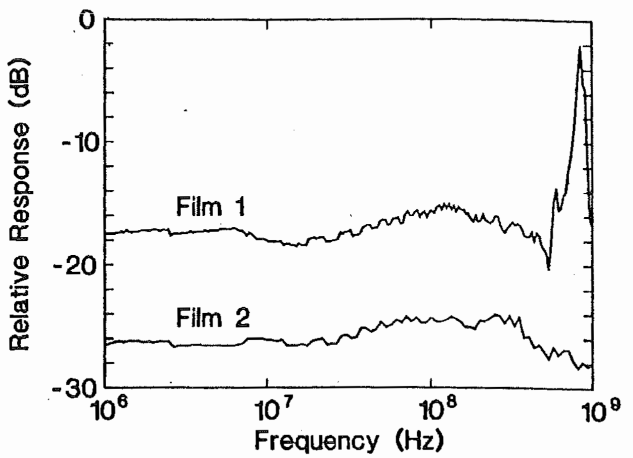

Fig. 4. Relative frequency response.

Figure 4 shows the measured frequency response of Films 1 and 2 in the waveguide geometry. The common structure observed in both films for frequencies less than 500 MHz is believed to be due to characteristics of the experimental system. Film 1 exhibits a resonance near 800 MHz. Film 2 exhibits a virtually flat frequency response up to 1 GHz. As evidenced by Fig. 4, both films exhibit much faster response in the optical waveguide geometry than in the geometry which favors domain wall motion.

IV. Hysteresis and Nonlinearity

To investigate the possibility of hysteresis at small fields, we employed a system like that shown in Fig. 1, but with two changes. The magnetic field was applied to the solenoid by an audio amplifier oscillating at ~100 Hz, and the signal from just one detector was fed to a digital oscilloscope. Figure 5 demonstrates the magneto-optic signal when Film 1 was subjected to a field amplitude $\mu_0 H_{max} \approx 0.15$ mT. The signal linearity and apparent lack of hysteresis support the domain rotation hypothesis. Figure 6 shows the response of the same film when the field strength was increased to a field amplitude $\mu_0 H_{max} \approx 2.0$ mT. The obvious hysteresis in this response indicates the

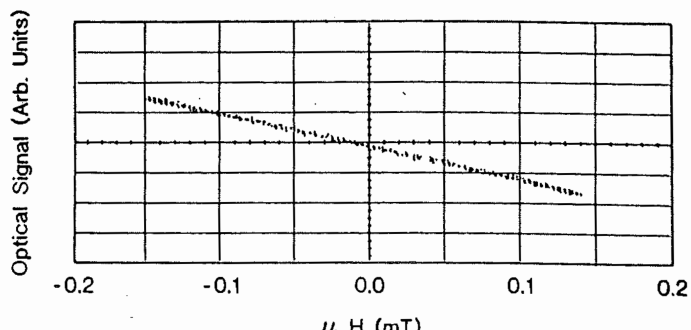

Fig. 5. Low-field magneto-optic response of Film 1.

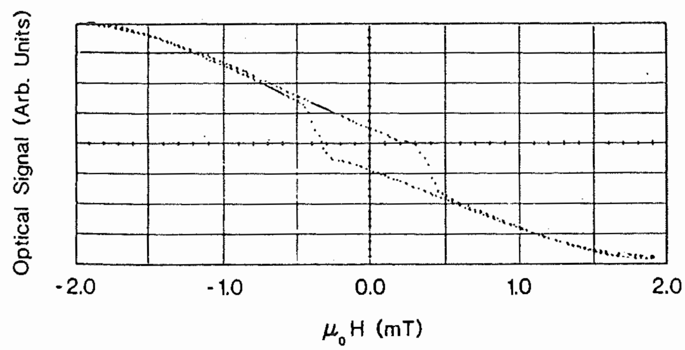

Fig. 6. Response of Film 1 for $\mu_0 H_{max} \approx 2$ mT.

presence of domain wall motion. This effect, although not well understood, might be prevented by defining the stripe domain pattern artificially. Hysteresis was apparent for field amplitudes $\mu_0 H_{max} \geq 0.2$ mT.

IV. Conclusion

From a fundamental viewpoint, iron garnet films employed in an optical waveguide geometry are ideal materials for magneto-optic magnetic field sensing. Large values of saturation Faraday rotation (achieved with bismuth substitution) and relatively long path lengths yield high sensitivity. Linear birefringence, which reduces sensitivity, can, in principle, be made negligible [6]. Data presented here show the superior frequency response of the waveguide geometry and suggest the possibility of eliminating hysteresis, which would permit sensitive dc measurements. The main difficulty with these materials is simply getting light into and out of the films efficiently. On the other hand, existing techniques can be employed to efficiently couple the optical inputs and outputs to optical fibers [1-3].

References

[1] Kaoru Matsuda and Satoshi Ishizuka, "Integration of a Faraday rotator and a mode selector for a magnetic field sensor," *Appl. Phys. Lett.*, vol. 55, pp. 610–612, 1989.

[2] Hans Sohlström and Kjell Svantesson, "A waveguide based fibre optic magnetic field sensor with directional sensitivity," *SPIE*, vol. 1511, pp. 142–148, 1991.

[3] R. Wolfe and R. A. Lieberman, "Fiber optic magnetic field sensor based on domain wall motion in garnet film waveguides," *Appl. Phys. Lett.*, vol. 58, pp. 1733–1736, 1991.

[4] R. Wolfe, E. M. Gyorgy, R. A. Lieberman, V. J. Fratello, S. J. Licht, M. N. Deeter, and G. W. Day, "High frequency magnetic field sensors based on the Faraday effect in garnet thick films," *Appl. Phys. Lett.*, vol. 60, pp. 2048–2050, 1992.

[5] See, for example, G. W. Day and A. H. Rose, "Faraday effect sensors: The state of the art," *SPIE*, vol. 985, pp. 138–150, 1988.

[6] R. Wolfe, V. J. Fratello, and M. McGlashan-Powell, "Elimination of birefringence in garnet films for magneto-optic waveguide devices," *Appl. Phys. Lett.*, vol. 51, pp. 1221–1223, 1987.