Domain effects in Faraday effect sensors based on iron garnets

M. N. Deeter

Domain-induced diffraction effects produced by two iron garnet thick films and two bulk crystals are compared. The thick films, characterized by a serpentine magnetic domain structure, produced nonlinear response functions; this is in qualitative agreement with a one-dimensional diffraction model. Bulk iron garnet crystals, which exhibited a complex three-dimensional domain structure, produced qualitatively similar effects that diminished with increasing crystal length. Differential signal processing resulted in a linear signal for the thick films and a primarily sinusoidal response for the bulk crystals.

1. Background

The sensitivity of Faraday effect sensors based on iron garnet bulk crystals[1–3] and epitaxial films[3–7] is much greater than the sensitivity of Faraday effect sensors based on diamagnetic and paramagnetic materials. However, because of the action of domain walls, iron garnets can exhibit hysteresis and nonlinear behavior. Such effects are completely eliminated only when the material is magnetically saturated as the result of a bias field.[2] This technique typically requires a permanent magnet, which adds to the size and weight of the sensor and may perturb the field to be measured. More simply, these domain effects can nearly be eliminated in uniaxial iron garnet films exploited in an optical waveguide geometry.[6] This geometry favors domain rotation over domain wall motion as the primary response to in-plane magnetic fields. Hysteresis is negligible in this arrangement because domain rotation, unlike domain wall motion, is generally reversible. Alternatively, the perpendicular film geometry considered here is simpler and exhibits potentially advantageous effects that are not possible in the waveguide geometry.

To a large degree, domain effects in bulk iron garnet crystals are minimized when the lateral dimensions of the probing light beam are much greater than the average domain size.[2] The success of this technique is apparently due to the three-dimensional spatial averaging that occurs when the probing light beam samples a statistically large number of domains. Domain effects play a much larger role in iron garnet films, specifically in thin films with perpendicular (uniaxial) magnetic anisotropy. Such films typically exhibit two-dimensional domains that are alternately magnetized up and down with respect to the surface. In the demagnetized state, these two types of domains are often interwoven in a complex serpentine pattern in which each type of domain covers an equal area. When an external magnetic field is applied perpendicular to the film, the domains for which the magnetization is parallel to the applied field grow (by domain wall motion) at the expense of the other domains, which contract.

Optically, these films behave as two-dimensional binary phase gratings.[7–9] For the simplest case of parallel stripe domains, the far-field diffraction pattern consists of an undeviated zeroth-order beam and a set of symmetrically positioned higher-order beams dispersed in a plane perpendicular to that of the stripe domains. Both the polarization states and the relative intensities of the various diffracted orders vary with the saturation Faraday rotation, $\theta_{F,\mathrm{sat}}$, and the net magnetization, M/M_{sat}. For optical fiber sensors, the behavior of the zeroth-order diffracted beam is most relevant, as the deflected higher-order beams will tend to be spatially filtered when the light is coupled into the fiber or fibers that return the light to the detection system.

2. Experimental

A conventional polarimetric differential detection system was employed to investigate domain effects (see Fig. 1). The individual outputs of the differential

The author is with the Optoelectronics Division, National Institute of Standards and Technology, Boulder, Colorado 80303.
Received 7 January 1994.
0003-6935/95/040655-04$06.00/0.

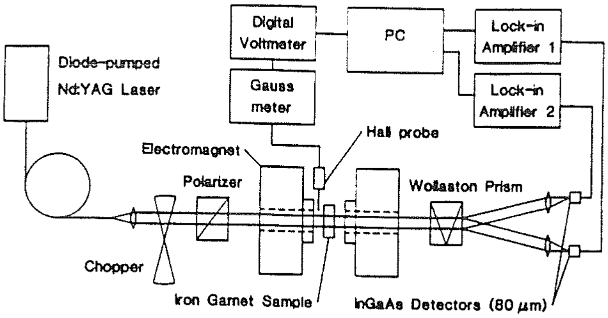


Fig. 1. Experimental system.

detection system were recorded separately so that both the zeroth-order intensity and polarization state could be monitored simultaneously. The source was a diode-pumped Nd:YAG laser operating at 1.3 μm. Its output was collimated (beam diameter $\phi \approx 3$ mm), polarized, and modulated with a chopper. The beam then passed through the garnet sample, which was placed in an electromagnet.

After leaving the sample, the zeroth-order beam propagated approximately 46 cm before reaching a polarizing beam splitter. The polarization axes of the beam splitter were oriented at ±45° with respect to the incident linear polarization state. Each of the resulting orthogonally polarized beams were then focused onto small InGaAs detectors ($\phi \approx 80$ μm). The small size of the detectors excluded all the higher-order diffracted light except that for which the diffraction angle was less than ~0.03°. Two lock-in amplifiers (referenced to the chopper frequency) recorded the outputs of the detectors as the applied magnetic field was swept through one complex cycle.

Through the use of Jones matrices to trace the polarization state of the zeroth-order beam, the intensities at each detector were calculated according to the domain diffraction model.[8] The predicted intensities are

$$I_{1,2}{}^0 = \frac{I_t}{2}\left[\cos^2\theta_{F,\mathrm{sat}} + \left(\frac{M}{M_{\mathrm{sat}}}\right)^2 \sin^2\theta_{F,\mathrm{sat}} \pm \left(\frac{M}{M_{\mathrm{sat}}}\right)\sin 2\theta_{F,\mathrm{sat}}\right], \quad (1)$$

where I_t is the total transmitted intensity in all orders and the plus or minus sign varies for the two detectors.

The sum and difference signals are then

$$I_s{}^0 = I_t\left[\cos^2\theta_{F,\mathrm{sat}} + \left(\frac{M}{M_{\mathrm{sat}}}\right)^2 \sin^2\theta_{F,\mathrm{sat}}\right], \quad (2)$$

$$I_d{}^0 = I_t \frac{M}{M_{\mathrm{sat}}} \sin 2\theta_{F,\mathrm{sat}}. \quad (3)$$

In contrast, the same signals for homogeneous (nondiffracting) materials are

$$I_{1,2}{}^H = \frac{I_t}{2}(1 \pm \sin 2\theta_F), \quad (4)$$

$$I_s{}^H = I_t, \quad (5)$$

$$I_d{}^H = I_t \sin 2\theta_F, \quad (6)$$

where θ_F (rather than M/M_{sat}) is the independent variable. These equations represent two extreme models against which we may test experimental data for the presence of domain diffraction effects. Comparing Eqs. (2) and (5), we see that domain effects produce a quadratic dependence of the sum signal on the applied field (assuming M/M_{sat} to be proportional to the applied field), whereas the sum signal of a homogeneous material is independent of the applied field. Equations (3) and (6) show that domain diffraction produces a differential signal that is linear with the applied field, whereas homogeneous materials produce a sinusoidal differential signal.

We compared the behaviors of two iron garnet thick films[5] and two bulk crystals. Their magnetic and physical properties are summarized in Table 1. The films are different in several respects compared with iron garnet films used in previous diffraction studies.[7–9] First, as shown and described in Ref. 5, the stripe domains in these films were not linear but rather arranged themselves in an irregular serpentine pattern. Second, the ratio of film thickness to domain stripe width (~6.4 for film 1 and ~8.6 for film 2) was considerably greater than that of previously studied films. As a result, the domains of both films exhibited a three-dimensional structure.[5] For example, cone-shaped domains of reverse magnetization were observed near both surfaces of film F1. Both the serpentine stripe pattern and the three-dimensional domain structure present in these films pose conditions that could limit the applicability of the diffraction model described above.

Table 1. Summary of Iron Garnet Samples

Parameter	Sample F1	Sample F2	Sample B1	Sample B2
Composition	$(BiTb)_3(FeGa)_5O_{12}$	$(BiY)_3Fe_5O_{12}$	$Y_3Fe_5O_{12}$	$Y_3Fe_5O_{12}$
M_{sat} (kA/m)	28	143	143	143
$\theta_{F,\mathrm{sat}}$ (°)	−45	−13.5	20	61
Thickness/length (mm)	0.32	0.06	1.0	3.0
Domain stripe width (μm)	50	7	—	—

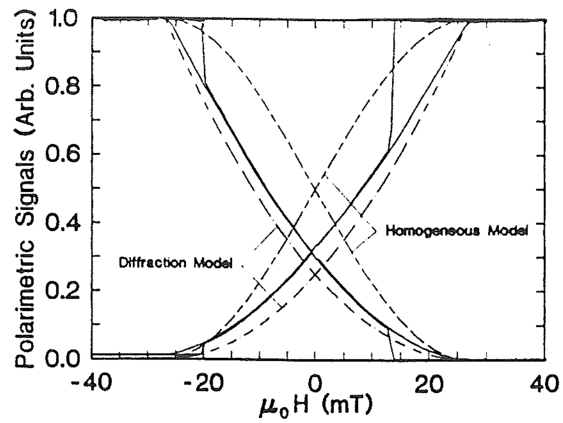


Fig. 2. Comparison of normalized polarimetric signal data (solid curve) for sample F1 with diffraction and homogeneous models.

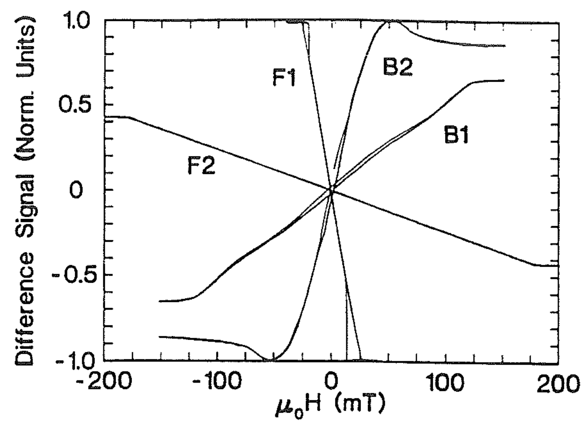


Fig. 4. Normalized difference signal data plotted versus applied magnetic field.

As observed by infrared microscopy, the domain structure of the bulk samples was much more complex than that of the films. Samples B1 and B2 were cut with their cylindrical axes parallel to the ⟨111⟩ and ⟨100⟩ crystallographic axes, respectively. Both cylinders were 5.0 mm in diameter.

3. Results and Discussion

Individual polarimetric signals I_1 and I_2 recorded for sample F1 are compared in Fig. 2 with theoretical signals calculated for both the zeroth-order diffractive model [Eq. (1)] and the homogeneous model [Eq. (4)]. Model calculations were based on values of 27 mT for $\mu_0 H_{sat}$ and 45° for $\theta_{F,sat}$ and assumed a linear relationship between M and H. The data clearly match the zeroth-order diffraction model better than the homogeneous model. The lack of even better agreement is probably due to the three-dimensional domain structure described above.

The sum and difference signals recorded for all four samples are shown in Figs. 3 and 4, respectively. With respect to the sum data, sample F1 exhibits a quadratic dependence with a minimum sum signal of ≈63%, which is reasonably close to the value predicted by Eq. (2) of 50%. (The apparent hysteresis shown by the F1 data was observed only after a saturating field was applied to the sample.) The sum minimum of sample F2 is ≈96.5%, in comparison with a theortical value of 94.5%. The bulk specimens exhibit sum minima of ≈94.2% (B1) and ≈97.5% (B2). These data indicate that a regular domain structure is not a prerequisite to the observation of diffractive effects. The longer sample (B2) exhibits a shallower minimum than the shorter sample. This might be because the greater number of domains in the longer specimen produce more spatial averaging and thus cause it to behave more like a homogeneous material. An analysis of the difference data is complicated because both models predict linear behavior for small values of $\theta_{F,sat}$. Thus only the difference signal data for samples F1 ($\theta_{F,sat} = -45°$) and B2 ($\theta_{F,sat} = 61°$) are significant. In agreement with the diffraction model, sample F1 exhibits a linear difference signal within the limits of saturation. Specimen B2, however, shows a sinusoidal dependence (before the onset of saturation), which is in agreement with the homogeneous model. (The opposite signs of the slopes of the differential signals of the films and bulk crystals are the result of opposite signs of $\theta_{F,sat}$.)

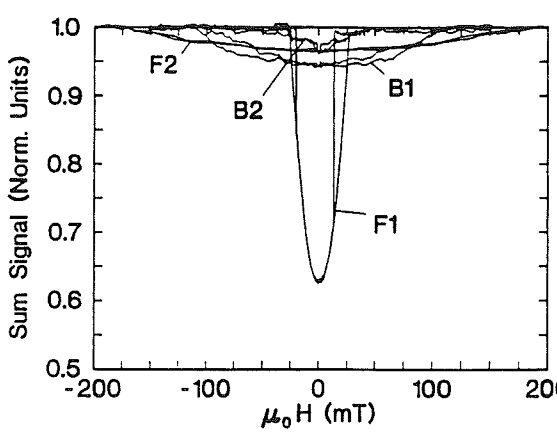


Fig. 3. Normalized sum signal data plotted versus applied magnetic field.

4. Conclusion

Domain-induced diffraction effects were compared for iron garnet thick films and bulk crystals. Thick films exhibiting serpentine magnetic domains produced nonlinear response functions; this is in qualitative agreement with a one-dimensional diffraction model. Bulk iron garnet crystals, which exhibited an even more complex three-dimensional domain structure, produced qualitatively similar effects that diminished with increasing crystal length. Differential signal processing resulted in a linear signal for the thick films and a sinusoidal response for the bulk crystals. These diffractive effects should be considered in the design of iron-garnet-based, fiber-optic magnetic field sensors in which coupling light from the film to the fiber could spatially filter all but the zeroth-order diffracted beam.

I thank R. Wolfe, V. J. Fratello, and S. J. Licht, all of AT&T Bell Laboratories, both for the iron garnet films and for valuable discussions.

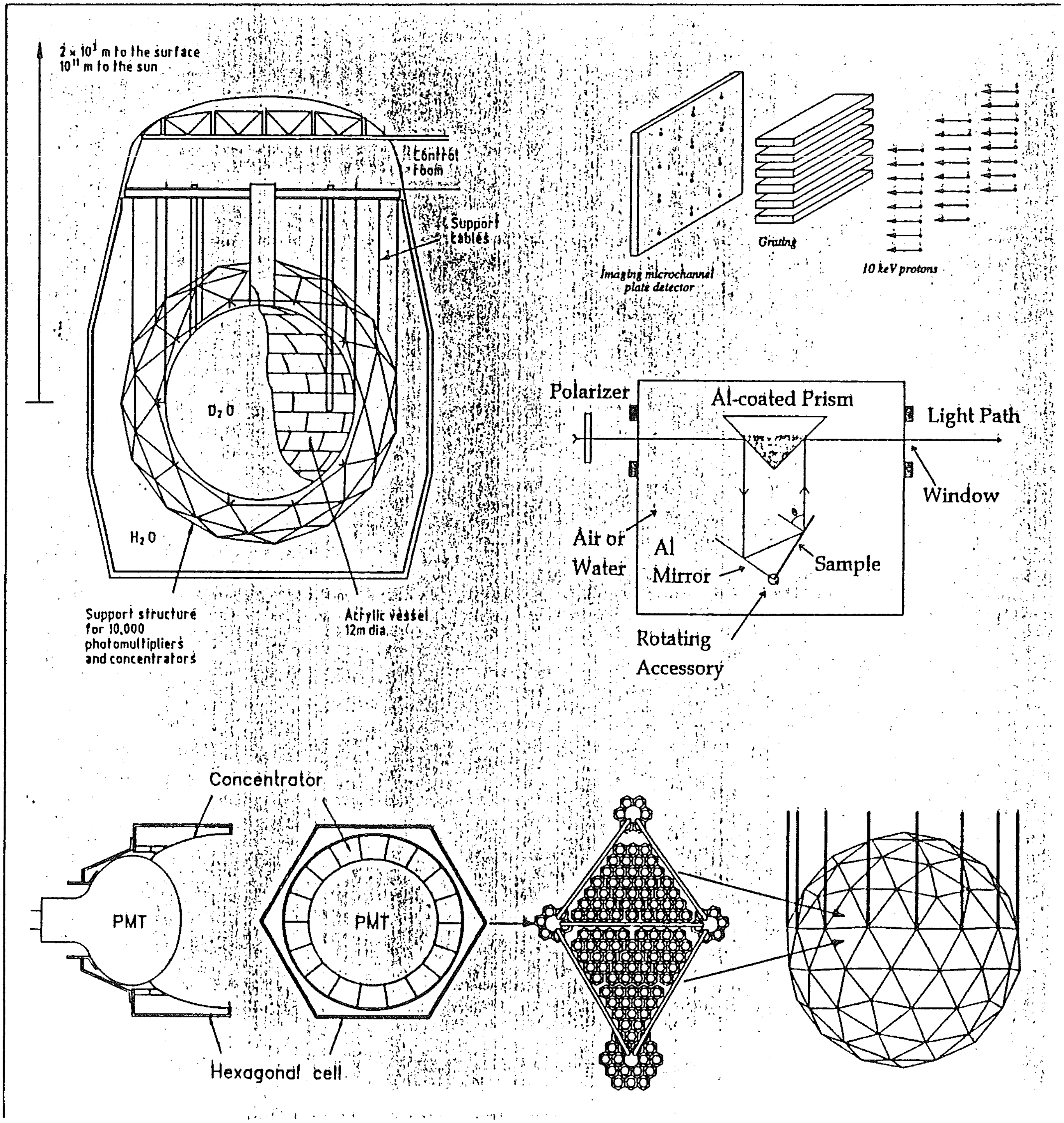
References

1. M. N. Deeter, A. H. Rose, and G. W. Day, "Faraday-effect magnetic field sensors based on substituted iron garnets," in *Fiber Optic and Laser Sensors VIII,* R. P. DePaula and E. Udd, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **1367,** 243–248 (1990).
2. U. Holm, H. Sohlström, and T. Brogårdh, "YIG-sensor design for fibre optical magnetic field measurements," in *2nd International Conference on Optical Fiber Sensors: OFS '84,* R. T. Kersten and R. Kist, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **514,** 333–336 (1984).
3. S. N. Barybin, A. N. Grigorenko, V. I. Konov, and P. I. Nikitin, "Magnetic field fibre-optical sensors based on Faraday effect," Sensors Actuators A **25–27,** 767–774 (1991).
4. R. Wolfe and R. A. Lieberman, "Fiber optic magnetic field sensor based on domain wall motion in garnet film waveguides," Appl. Phys. Lett. **58,** 1733–1735 (1991).
5. 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. **60,** 2048–2050 (1992).
6. M. N. Deeter, G. W. Day, R. Wolfe, and V. J. Fratello, "Magneto-optic magnetic field sensors based on uniaxial iron garnet films in optical waveguide geometry," IEEE Trans. Magn. **29,** 3402–3404 (1993).
7. T. Numata, M. Yao, S. Inokuchi, and Y. Sakurai, "Improved sensitivity in novel scheme of magneto-optical field sensor," IEEE Trans. Magn. **27,** 5393–5395 (1991).
8. T. Numata, H. Tanaike, S. Inokuchi, and Y. Sakurai, "Nonlinearity of Faraday loops," IEEE Trans. Magn. **26,** 1358–1360 (1990).
9. D. I. Sementsov, R. M. Grechishkin, and Y. N. Zubkov, "Magneto-optic diffraction by a stripe domain structure with wavy walls," J. Phys. D. **24,** 2210–2214 (1991).

Applied Optics

1 FEBRUARY 1995

OPTICAL TECHNOLOGY



 Applied Optics (ISSN 0003-6935) is published three times a month by the Optical Society of America, 2010 Massachusetts Avenue, NW, Washington, DC 20036-1023. CODEN: APOPAI. USPS Publication No. 879520. 1995 subscription rates (domestic) per year (paper or microfiche): $89.00 for OSA members; nonmember and library subscriptions: $1220.00. Second-class postage paid at Washington, DC 20066-9998 and at additional mailing offices POSTMASTER: Send address changes to *Applied Optics*, 2010 Massachusetts Avenue, NW, Washington, DC 20036-1023. **Subscriptions, missing copies, and change of address:** Optical Society of America, Fulfillment Services, 2010 Massachusetts Avenue, NW, Washington, DC 20036-1023; (202) 223-8130; FAX (202) 223-1096. Back number, single-issue, and foreign rates available on request. *Applied Optics*® is a registered trademark of OSA.