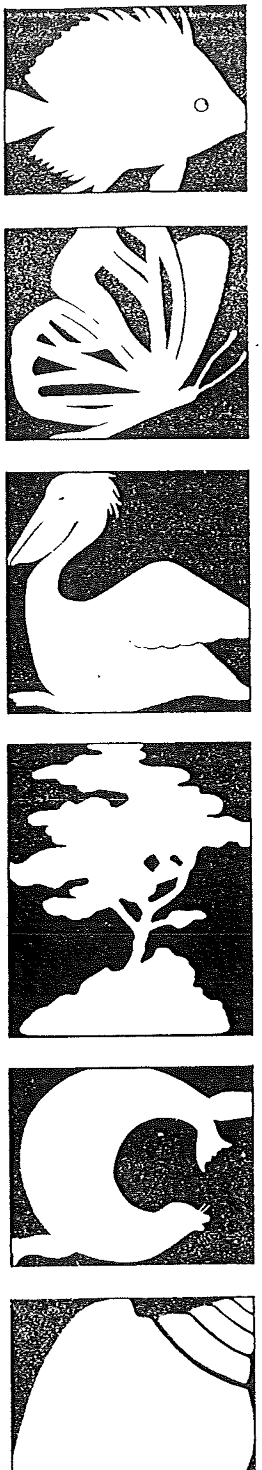

8th Optical Fiber Sensors Conference
January 29-31, 1992

Post Deadline Papers

Monterey Marriott
Monterey, California

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Domain Effects in Faraday Effect Sensors

Based on Iron Garnets

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Abstract

Domain effects in Faraday effect fiber-optic magnetic field sensors which employ thick films and bulk crystals of iron garnets produce fundamentally different responses. Iron garnet films with uniaxial magnetic anisotropy exhibit domain-induced diffraction which produces a nonlinear signal even in films for which the net magnetization is exactly linear with the applied field. Fortunately, differential detection eliminates this nonlinearity. Moreover, differential detection applied to these films produces a signal which is linear regardless of the value of the saturation Faraday rotation. This behavior is quite unlike that of other Faraday effect sensors, which exhibit sinusoidal output signals. Domain effects in bulk crystals, which exhibit three-dimensional domain structure, are less evident than in films.

Background

The sensitivity of Faraday effect sensors based on iron garnet bulk crystals[1,2] and epitaxial films[3-5] is much greater than the sensitivity of Faraday effect sensors based on diamagnetic and paramagnetic materials. However, because of the presence of magnetic domains, iron garnets can exhibit hysteresis and nonlinear behavior. Such effects are completely absent 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. Moreover, the bias field itself produces a different type of nonlinear response.

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 due to the three-dimensional spatial averaging which occurs when the probing light beam samples a statistically large number of domains. Domain effects play a much larger role in iron garnet films and, specifically, thin films with perpendicular (uniaxial) magnetic anisotropy. Such films exhibit two-dimensional domains which are magnetized either up or down with respect to the surface. In the demagnetized state, these two types of domains are 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 with their magnetization parallel to the applied field grow at the expense of the other domains, which contract. Optically, these films behave as two-dimensional phase gratings and produce strong diffraction effects.[5,6]

The diffraction theory for these materials has been solved exactly for the case of parallel stripe domains. The resultant far-field diffraction pattern consists of an undeviated zero-order beam and a set of symmetrically positioned higher-order beams. Both the polarization states and the relative intensities of the various diffracted orders vary with the saturation Faraday rotation $\Theta_{F,sat}$ and the net magnetization M/M_{sat}. For optical fiber sensors, the behavior of the zero-order diffracted beam is most relevant because the deflected higher-order beams will tend to be spatially filtered when the light is coupled into the fiber or fibers which return the light to the detection system.

Experimental

A conventional polarimetric differential detection system was employed to investigate domain effects. The individual outputs of the differential detection system were recorded separately so that both the zero-order intensity and polarization state could be monitored simultaneously. The source was a diode-pumped YAG laser operating at 1.3 μm. Its output was collimated (the 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 zero-order beam propagated approximately 46 cm before reaching a polarizing beamsplitter. The polarization axes of the beamsplitter were oriented at $\pm 45^\circ$ with respect to the incident linear polarization state. The resulting orthogonally polarized beams were each 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 complete cycle.

Using Jones matrices to trace the polarization state of the zero-order beam, the intensities at each detector were calculated according to the domain diffraction model.[6] The predicted intensities are

$$I^0_{1,2} = \frac{I_t}{2}[\cos^2\theta_{F,sat} + (\frac{M}{M_{sat}})^2\sin^2\theta_{F,sat} \pm (\frac{M}{M_{sat}})\sin 2\theta_{F,sat}] \ , \tag{1}$$

where the ± sign varies for the two detectors. The sum and difference signals are

$$I^0_s = I_t\,[\cos^2\theta_{F,sat} + (\frac{M}{M_{sat}})^2\sin^2\theta_{F,sat}] \tag{2}$$

and

$$I^0_d = I_t\,\frac{M}{M_{sat}}\sin 2\theta_{F,sat} \ . \tag{3}$$

In contrast, the same signals for homogeneous materials are

$$I^H_{1,2} = \frac{I_t}{2}(1 \pm \sin 2\theta_F) \ , \tag{4}$$

$$I^H_s = I_t \ , \tag{5}$$

and

$$I^H_d = I_t \sin 2\theta_F \ , \tag{6}$$

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. These effects will manifest themselves in two ways. 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 which is linear with the applied field, whereas homogeneous materials produce a sinusoidal differential signal. These behaviors are only distinguishable for sufficiently large values of Θ_F.

Two single-sided thick films[7] and two bulk crystals of iron garnet were characterized. For thick film sample F1, M_{sat} was 28 kA/m, $\Theta_{F,sat}$ was -45°, the thickness was 320 μm, and the average domain stripe width was 50 μm. For thick film specimen F2, M_{sat} was 143 kA/m, $\Theta_{F,sat}$ was -13.5°, the thickness was 60 μm, and the average domain stripe width was 7 μm. Both films exhibited uniaxial magnetic anisotropy but also exhibited some degree of three-dimensional domain structure.[7] Both bulk samples were yttrium iron garnet (YIG) cylinders 5 mm in diameter with values of M_{sat} of 143 kA/m. Specimen B1 was 1 mm long and exhibited a value of $\Theta_{F,sat}$ of 20° whereas sample B2 was 3 mm long and exhibited a value of $\Theta_{F,sat}$ of 61°.

Results and Discussion

The sum and difference signals recorded for the four samples are shown in Figures 1 and 2. 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 of 50% predicted by Eq. (2). (The apparent hysteresis shown by the F1 data was only observed when a saturating field was applied to the sample.) The sum minimum of Sample F2 is ≈ 96.5% in comparison with a theoretical value of 94.5%. The bulk specimens exhibited sum minima of ≈ 94.2% (B1) and ≈ 97.5% (B2) despite their three-dimensional domain structure. The longer sample (B2) exhibits a shallower minimum than the shorter sample. This is probably because the greater number of domains in the longer specimen produce a higher degree of spatial averaging and thus cause it to behave more like a homogeneous material. 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 relevant. 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, which agrees 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 $\Theta_{F,sat}$.)

Conclusion

Domain-induced diffraction in Faraday effect fiber-optic sensors which employ thick films of iron garnet produces a nonlinear response. Bulk iron garnet crystals, which exhibit three-dimensional domain structure, produce smaller domain effects. A diffraction model for the zero-order diffracted beam predicts that the output of a single-output-channel sensor will exhibit a quadratic dependence with the applied field. However, the same model predicts that differential detection will result in a signal which is directly proportional to M/M_{sat}, regardless of the value of saturation Faraday rotation. Experiments on two thick iron garnet films confirmed these predictions qualitatively. The signal linearity exhibited by this arrangement is significantly better than that of conventional Faraday effect sensors, which normally exhibit linearity only over a small part of a larger sinusoidal curve.

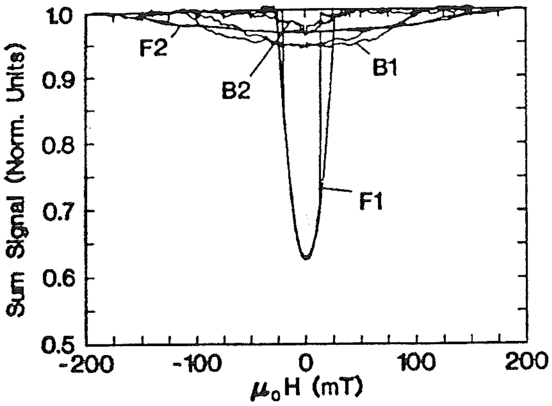

Figure 1. Normalized sum signal versus applied magnetic field.

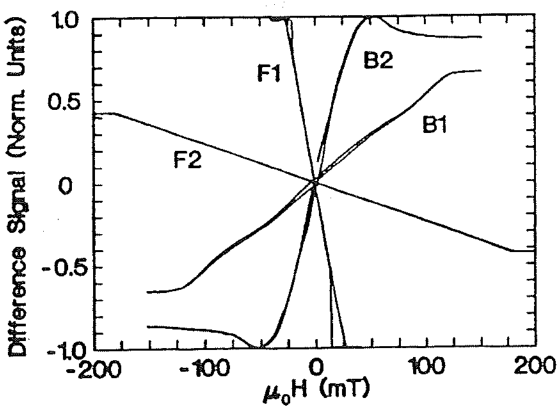

Figure 2. Normalized difference signal versus applied magnetic field.

Acknowledgment

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

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