Sensitivity limits to ferrimagnetic Faraday effect magnetic field sensors

M. N. Deeter, A. H. Rose, and G. W. Day
Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, Colorado 80303

S. Samuelson
Deltronic Crystal Industries, Inc., 60 Harding Avenue, Dover, New Jersey 07801

In general, the sensitivity of ferrimagnetic Faraday effect magnetic field sensors is a function of both the crystal geometry and composition. The geometrical dependence of the sensitivity in nonellipsoidal crystals, such as cylinders, is complicated by their spatially nonuniform demagnetizing factors. We compare sensitivity data obtained from a variety of cylindrical iron garnet samples with models which predict the effective demagnetizing factor N_{eff} as a function of the length-to-diameter ratio. With respect to composition, we present experimental results of sensitivity vs diamagnetic substitution (x) in the iron garnet series $Y_3Fe_{5-x}Ga_xO_{12}$. As expected, the sensitivity rises sharply as x approaches the compositional compensation point.

INTRODUCTION

Bulk crystals of ferrimagnetic iron garnets make excellent sensing elements for Faraday effect magnetic field sensors.[1–4] The sensitivity of these crystals, defined as the differential Faraday rotation per unit applied magnetic field, can be enhanced by several methods. These techniques can be classified as being either geometrical or compositional.

Ideally, the sensitivity S of ferrimagnetic sensing elements is given by[4]

$$S = d\Theta_F/dH = \Theta_F^{\mathrm{sat}}/H_{\mathrm{sat}}, \tag{1}$$

where Θ_F^{sat} is the saturation Faraday rotation and H_{sat} is the saturation field (the applied field at which the sample magnetization becomes saturated). In the case of ellipsoidal specimens, for which the demagnetizing factor N is spatially uniform,

$$H_{\mathrm{sat}} = M_{\mathrm{sat}}(N + 1/\chi) \approx N M_{\mathrm{sat}}, \tag{2}$$

where M_{sat} is the saturation magnetization and we have assumed that the susceptibility $\chi \gg 1$. For any other shape, N varies as a function of both position in the specimen and local susceptibility. The susceptibility, in turn, varies as a function of the local magnetic field H_{loc}. Together, these factors prevent the direct use of Eqs. (1) and (2) to accurately predict the sensitivity of bulk crystal specimens with practical geometries, such as cylinders.

Both Θ_F^{sat} and M_{sat} are sensitive to even small changes of the iron garnet composition. Thus, the sensitivity of iron garnets defined in Eq. (1) may be enhanced by replacing certain ions in some host crystal, such as yttrium iron garnet ($Y_3Fe_5O_{12}$, abbreviated YIG), with different ions having different effects. For example, substituting Bi ions into Y sites in YIG greatly increases Θ_F^{sat}.[5,6] On the other hand, diamagnetic substitution can be used to decrease M_{sat}, which also increases S.[4,7]

EXPERIMENT

In order to test models which might be useful in predicting the performance of ferrimagnetic Faraday effect sensors, we have collected data on a variety of diamagnetically substituted iron garnets ($Y_3Fe_{5-x}Ga_xO_{12}$, $0 \leqslant x \leqslant 0.98$) with cylindrical geometries and various values of the length-to-diameter ratio L/D. Single crystals were synthesized by the high-temperature solution growth technique ("flux method"). Melts of 6–7 kg were made using flux composed primarily of lead oxide and lead fluoride. Crystals were grown by spontaneous nucleation in the temperature range of 1100–1180 °C over a period of 18–22 days. The crystals were separated from the flux by decanting the liquid and allowing the batch to cool rapidly to room temperature. Cylindrical samples of high crystalline and optical quality were fabricated from each batch and the ends were optically polished.

For each sample, the Faraday rotation was measured as the magnetic field was swept through one complete cycle. The peak strength of the field was always large enough to saturate the Faraday rotation. Rotation measurements were made at a source wavelength of 1.3 μm with a differential detection system consisting of a polarization beam splitter and two InGaAs photodetectors. A chopper and two lock-in amplifiers were used to record the optical intensities which were then converted to values of Faraday rotation by a computer interfaced to the lock-in amplifiers.

GEOMETRICAL EFFECTS

Figure 1 shows typical data obtained from a sample of composition $Y_3Fe_{4.53}Ga_{0.47}O_{12}$, length 2.48 mm, and diameter 3.00 mm. The general characteristics of these data are a linear region at low fields followed by a nonlinear region which continues until the specimen is saturated. For each set of data, we recorded S (the slope of the linear region), H_l (the boundary of the linear region), and Θ_F^{sat}.

For nonellipsoidal shapes, we assume that Eq. (2) is still valid provided that we replace N by N_{eff}, where N_{eff} is the effective demagnetizing factor and represents a volume

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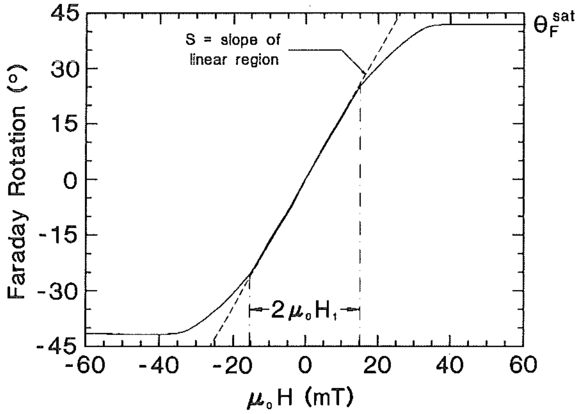

FIG. 1. Faraday rotation vs applied magnetic field exhibited by a sample of composition $Y_3Fe_{4.53}Ga_{0.47}O_{12}$, length 2.48 mm, and diameter 3.00 mm. S, H_1, and Θ_F^{sat} are defined in the text.

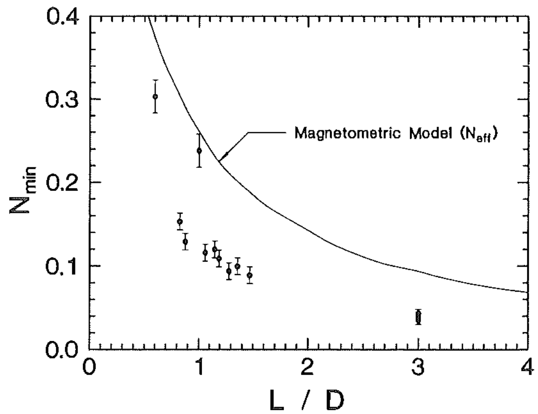

FIG. 3. Dependence of the minimum local demagnetizing factor on the length-to-diameter ratio. See Eq. (4).

average of N. This approximation assumes that $\chi \gg 1$, and thus becomes invalid when any part of the body begins to saturate. In this case,

$$N_{\text{eff}} = \Theta_F^{\text{sat}} / S M_{\text{sat}}. \tag{3}$$

Plotting experimentally obtained values of N_{eff} vs L/D allows us to directly examine the validity of two approximate geometrical models. To calculate N_{eff} for each sample, values of Θ_F^{sat} and S were taken from rotation-vs-field data, and values of M_{sat} were determined by ferrimagnetic resonance measurements on spherical samples taken from the same crystal growth run as the cylindrical samples. Values of M_{sat} ranged from ~ 24 ($Y_3Fe_{4.02}Ga_{0.98}O_{12}$) to ~ 141 kA/m ($Y_3Fe_5O_{12}$).

Experimental values of N_{eff} are compared with the results of two models for demagnetizing factors in Fig. 2. The equivalent-ellipsoid model[8] approximates the cylinder as an ellipsoid having the same value of L/D. The magnetometric cylinder model[9] employs a two-dimensional algorithm for calculating the volume-averaged demagnetizing factor of cylinders for any given value of χ. The magnetometric curve in Fig. 2 corresponds to the case $\chi = \infty$. Not surprisingly, the magnetometric curve provides a much better fit to the data than does the ellipsoid model.

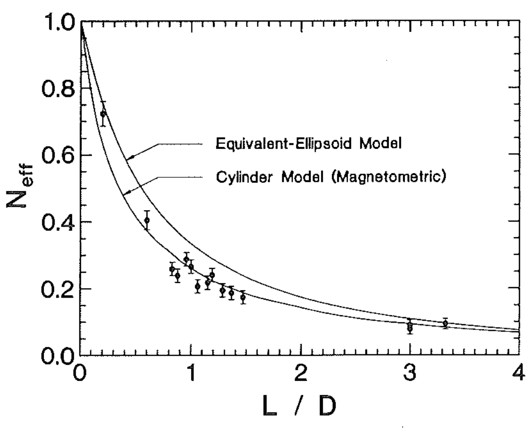

FIG. 2. Dependence of the effective demagnetizing factor on the length-to-diameter ratio. See Eq. (3).

For constant χ, the magnetization and the Faraday rotation exhibited by a cylindrical sample should increase linearly with the applied magnetic field. As the field is increased further, however, some point within the sample will eventually become saturated ($M = M_{\text{sat}}$, $\chi = 0$). The physical location of this point is that position within the body which possesses the minimum local demagnetizing factor N_{min}. According to this model, data of Faraday rotation vs magnetic field should begin to become nonlinear at a field H_1, where

$$H_1 = N_{\text{min}} M_{\text{sat}}. \tag{4}$$

Experimental values of N_{min} (H_1/M_{sat}) are plotted against L/D in Fig. 3. The data are compared with the previously defined magnetometric model curve of N_{eff} (calculated for the case $\chi = \infty$) since no data exists in the literature directly regarding N_{min} for cylindrical bodies. The magnetometric model is to be considered only as an upper limit to N_{min}.

With the exception of a single datum (at $L/D = 1.0$), the experimental values of N_{min} exhibit a well-defined trend which follows a curve well below N_{eff}. At least two factors probably contribute to the fact that N_{min} is substantially less than N_{eff}. First, the local demagnetizing factor varies considerably within cylindrical bodies.[9] Another factor, however, is that our model of saturation is probably unrealistic. For example, it is unlikely that $\chi(H_{\text{loc}})$ changes discontinuously from some large value to 0 as H_{loc} is increased. This effect, like that of the varying demagnetizing factor, would tend to reduce H_1. The cause for the behavior of the datum at $L/D = 1.0$ is unknown. Empirically, we find that for $L/D > 1$, $N_{\text{min}} \approx 0.5 N_{\text{eff}}$, where N_{eff} is given by the magnetometric model.

COMPOSITIONAL EFFECTS

Compositionally, S may be optimized by selecting materials which maximize the ratio $\Theta_F^{\text{sat}}/M_{\text{sat}}$. Diamagnetic substitution, in which certain Fe ions (primarily in the tetrahedral sublattice) are replaced by diamagnetic ions,

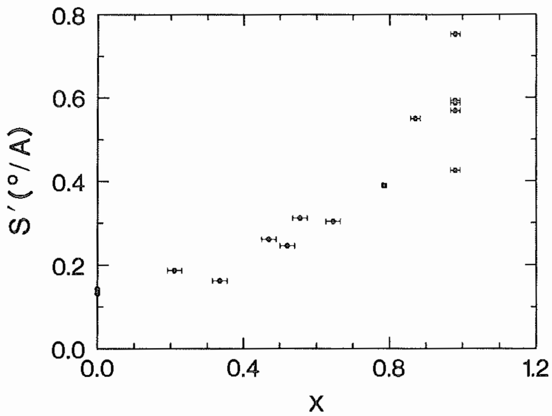

FIG. 4. Compositional dependence of the normalized sensitivity S'. See Eq. (6).

such as Ga, has already successfully been used to increase this ratio.[4,7] Generally speaking, diamagnetic substitution produces a slight decrease in $\Theta_F^{\rm sat}$ and a much larger decrease in $M_{\rm sat}$, resulting in a significant increase in their ratio. Attempting to model this effect is difficult, however, because of the lack of data regarding the dependence of $\Theta_F^{\rm sat}$ at 1.3 μm on composition.

According to Eq. (3),

$$\Theta_F^{\rm sat}/M_{\rm sat}=SN_{\rm eff}. \tag{5}$$

Since $\Theta_F^{\rm sat}$ and S are both proportional to L, the length of the crystal, we divide both sides of Eq. (5) by L to obtain the normalized sensitivity S' which is only a material-dependent quantity:

$$S'=\Theta_F^{\rm sat}/LM_{\rm sat}=SN_{\rm eff}/L. \tag{6}$$

This parameter is equivalent to the Verdet constant which quantifies the Faraday effect in diamagnetic materials. In SI units, S' has units of degrees of arc per ampere. Calculated values of $SN_{\rm eff}/L$ (in which values of $N_{\rm eff}$ were given by the magnetometric model) are plotted against x in Fig. 4. The S' data generally exhibit a sharp rise as x approaches the compositional compensation point[10] ($x\approx 1.3$) where $M_{\rm sat}$ vanishes. The cause of the scattering of the S' data for $x=1.0$ is not fully understood but probably results from the wide range of L/D values (0.20–3.33) represented in the $x=1.0$ data.

CONCLUSION

Our data do not indicate the presence of any fundamental limit to the sensitivity of ferrimagnetic Faraday effect sensors. We anticipate that sensitivities greater than those presented here can still be achieved either with smaller demagnetizing factors or compositions which more closely approach the compositional compensation point. There are tradeoffs, however. Both of the techniques presented here tend to reduce H_1, which represents the maximum field which produces a linear rotation. Moreover, as $M_{\rm sat}$ is reduced, so is the effective force which moves the domain walls.[11] Thus, the effects of coercivity, which were not apparent in the data presented here, might become more evident as the compositional compensation point is approached. Nevertheless, these techniques, combined with those that directly increase $\Theta_F^{\rm sat}$ (such as Bi substitution[5,6]) should be expected to substantially improve the performance of these sensors.

ACKNOWLEDGMENTS

We thank R. B. Goldfarb and J. A. Brug for their invaluable insight into demagnetizing phenomena. This paper represents work of the U. S. Government and is not subject to copyright.

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