

Faraday-effect magnetic field sensors based on substituted iron garnets

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ABSTRACT

The class of ferrimagnetic materials known as substituted iron garnets display characteristics which make them suitable for applications of magnetometry requiring high sensitivity, high spatial resolution, or high speed. Diamagnetic substitution, in which specific iron ions are replaced by diamagnetic ions, reduces the saturation magnetization and increases the sensitivity. We find that the sensitivity of a composition of gallium-substituted yttrium iron garnet is six times greater than of pure yttrium iron garnet. The noise-equivalent magnetic field for a sample of this material has been measured as approximately $100 \text{ pT}/\sqrt{\text{Hz}}$.

1. INTRODUCTION

The Faraday effect provides an effective means for sensing both magnetic fields and electric current.¹ Such sensors are particularly attractive in applications which require stability, speed, or compatibility with electrically hostile environments. Their stability derives from the rather simple polarimetric (as opposed to interferometric) detection systems which they typically employ. Their frequency response is usually limited only by the transit time of the light through the sensing element. Furthermore, because these sensors are generally passive and can usually be constructed from dielectric materials only, they can be used in environments which expose the sensors to high voltages and electromagnetic interference. These same properties are also important in applications which require that the sensor not significantly perturb the field being measured.

Faraday-effect magnetic field sensors have been constructed from diamagnetic, paramagnetic, and ferrimagnetic materials. Diamagnetic materials, including optical fibers, various optical glasses, and certain crystalline materials, are useful because of their wide availability and insensitivity to temperature fluctuations. With few exceptions, however, diamagnetic materials have limited sensitivity and are typically useful only for measuring medium- to high-strength magnetic fields. Paramagnetic materials, such as various doped glasses, are more sensitive than diamagnetic materials, but exhibit a much stronger temperature dependence which often limits their utility.

More recently, increasing attention has been given to the class of ferrimagnetic materials known as iron garnets.²⁻⁶ Although the magnetic characteristics of these materials make them considerably more complicated than diamagnetic and paramagnetic materials, they hold the promise of being the most sensitive. In addition, potential problems with iron garnets, such as nonlinear response, hysteresis, and temperature dependence, do not appear to be insurmountable.

In ferrimagnetic materials, an applied magnetic field tends to align the magnetic dipoles of the individual domains which make up the material. Linearly polarized light propagating parallel to the applied field undergoes Faraday rotation proportional to the net magnetization. As the applied field is increased, eventually all the domains are aligned with the applied field and the material becomes magnetically saturated. At this point, the Faraday rotation is maximum. Below this point, the magnetization and Faraday rotation are ideally linear with applied field, as in Fig. 1. In the ideal case, the slope $d\theta_F/dH$ of this curve, defined as the sensitivity, is simply given by the ratio of the saturation Faraday rotation θ_F^{sat} to the saturation field H_{sat} .

The quantities θ_F^{sat} and H_{sat} both depend on the specific iron garnet composition and temperature. In addition, θ_F^{sat} depends on the wavelength of the light and H_{sat} on the demagnetization factor, which is a function of the sensor shape. Typically, θ_F^{sat} and H_{sat} behave quite differently with respect to changes of composition and temperature. For example, certain diamagnetic substitutions in yttrium iron garnet (YIG) reduce H_{sat} much more than θ_F^{sat} . Thus, the fact that θ_F^{sat} and H_{sat} behave differently with respect to changes of composition and temperature is important in that it should allow a certain degree of control over both the sensitivity and its temperature dependence. To better understand how such a control may be implemented, models which satisfactorily describe the temperature and composition dependences of θ_F^{sat} and H_{sat} are needed.

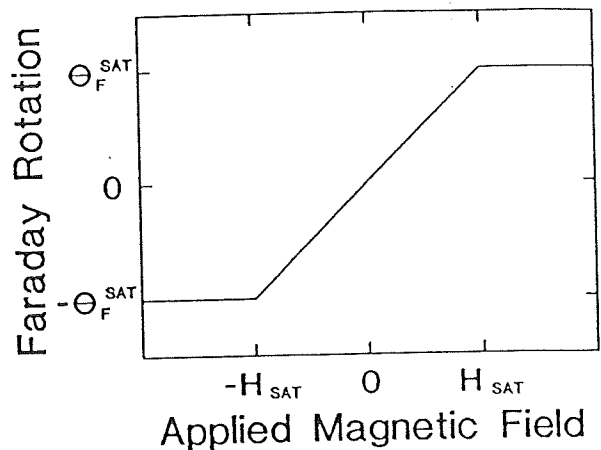


Figure 1. Ideal response of ferrimagnetic sensor to applied magnetic field.

2. FERRIMAGNETIC PROPERTIES OF IRON GARNETS

For a given iron garnet composition, H_{sat} is given in SI units by

$$H_{sat}(T) = N_D M_{sat}(T), \quad (1)$$

where N_D is the demagnetization factor, M_{sat} is the material's saturation magnetization, and T is the temperature. The demagnetization factor, which depends primarily on shape, accounts for the difference between the magnetic field applied to a magnetic body and the actual field within the body. M_{sat} is given by summing the magnetic moments of the tetrahedral, octahedral, and dodecahedral magnetic sublattices present in the iron garnet. For some iron garnets, though, only two of these sublattices actually contribute to M_{sat} . For example, iron garnets in which the dodecahedral sublattice is occupied by diamagnetic ions (such as the Y^{3+} ion in $Y_3Fe_5O_{12}$, also known as YIG) have two opposed magnetic sublattices: the tetrahedral or d sublattice, containing 3 Fe^{3+} ions per formula unit, and the octahedral or a sublattice, containing 2 Fe^{3+} ions per formula unit. Thus, for YIG,

$$M_{sat}(T) = M_d(T) - M_a(T), \quad (2)$$

where M_d and M_a are the magnetizations of the tetrahedral and octahedral sublattices, respectively.⁷ Other iron garnets, such as the rare-earth iron garnets, do have magnetic dodecahedral sublattices and therefore require a third contribution on the right side of Eq. (2).⁷ On the other hand, Eq. (2) is often valid for diamagnetically substituted iron garnets^{9,10} such as gallium-substituted YIG in which certain Fe^{3+} ions are replaced by diamagnetic ions such as Ga^{3+} . This technique is often used to reduce the magnetization of YIG because certain diamagnetic ions, such as Ga^{3+} , which dilute the magnetization, often preferentially substitute for Fe^{3+} ions in one sublattice rather than the other.¹⁰ In fact, for many substituting ions, there exists a "compensation composition" for which M_{sat} actually equals zero. This exact composition is, in general, dependent on temperature.

$M_d(T)$ and $M_a(T)$ have been determined for many iron garnets by fitting Néel's theory of ferrimagnetism to measured $M_{sat}(T)$ data.⁷⁻¹⁰ Generally, the problem is reduced to determining material-dependent constants known as the molecular field coefficients, from which $M_d(T)$ and $M_a(T)$ may be calculated numerically. The same technique has also been employed to determine the

composition-dependent molecular field coefficients of substituted iron garnets such as gallium-substituted yttrium iron garnet ($Y_3Ga_xFe_{5-x}O_{12}$ or Ga:YIG).^{9,10} In this case, knowledge of the precise distribution of the Ga^{3+} ions among the a and d sites is a prerequisite to determination of the molecular field coefficients.

3. MAGNETO-OPTICAL PROPERTIES OF IRON GARNETS

The standard model for the magneto-optical properties of iron garnets requires only a slight extension to the model for their magnetic properties. Magneto-optical effects in iron garnets originate from magnetic and electric dipole transitions which can be expressed in terms of the sublattice magnetizations.¹¹ Expressing the Faraday rotation in a power-series expansion of the sublattice magnetizations, one obtains¹¹

$$\theta_F^{sat} = \theta_F^0(T)[1 + pM_a(T)M_d(T) + \dots], \quad (3a)$$

where

$$\theta_F^0(T) = AM_a(T) + DM_d(T), \quad (3b)$$

A and D are the wavelength-dependent magneto-optical coefficients of the a and d sublattices, and p is the third-order magnetization term. Similar equations are used to describe the Faraday ellipticity.

4. SENSITIVITY OF IRON GARNETS

The sensitivity of materials which exhibit a dependence of Faraday rotation on applied field as shown in Fig. 1 is

$$S = d\theta_F/dH = \theta_F^{sat} / H_{sat}. \quad (4)$$

Substituting Eqs. (2) and (3) into Eq. (4), we find

$$S \approx [AM_a(T) + DM_d(T)] / [N_D(M_d(T) - M_a(T))], \quad (5)$$

where we have neglected the third-order magnetization term in θ_F^{sat} . Using established models for the composition and temperature dependences of the sublattice magnetizations and magneto-optical coefficients, we can thus model the composition and temperature dependence of the sensitivity of iron garnet sensors. The necessary parameters of the model are the molecular field coefficients, which are needed to calculate $M_d(T)$ and $M_a(T)$, and the magneto-optical coefficients A and D . Such a model was successfully demonstrated by Kamada, et al.,² who determined the composition of $(Tb_xY_{1-x})_3Fe_5O_{12}$ for which the temperature dependence of the sensitivity was a minimum at $1.15 \mu m$.

Unfortunately, little information regarding the composition dependence of either θ_F^{sat} or the magneto-optical coefficients of substituted iron garnets at $1.3 \mu m$ is available in the literature. This wavelength is important because of its position above the garnet absorption edge near $1 \mu m$, and because of the desirable characteristics of laser diodes which are available at this wavelength. This lack of magneto-optical data precludes the possibility of accurately predicting either the sensitivity or the temperature dependence of the sensitivity of arbitrary substituted iron garnet compositions.

5. EXPERIMENTAL RESULTS

We measured the sensitivity and temperature dependence of bulk single crystals¹² of both YIG and $Y_3Ga_{1.0}Fe_{4.0}O_{12}$. The YIG sample was 5 mm in diameter and 3 mm long, while the Ga:YIG

sample was 1 mm in diameter and 3 mm long. The demagnetization factors were approximately 0.476 and 0.109 for the YIG and Ga:YIG samples, respectively.¹³ We chose the particular composition of gallium-substituted YIG based on data which showed that it exhibited an 85% reduction in M_{sat} in comparison with pure YIG, but exhibited a decrease in e_F^{sat} of only about 35%.¹⁴ According to Eq. (4), this composition should increase the sensitivity by a factor of 4.3 with respect to pure YIG, given the same sensor length and demagnetization factor. Including the effects of the different demagnetization factors, the sensitivity of the Ga:YIG sample should be approximately 19 times greater than of the pure YIG sample.

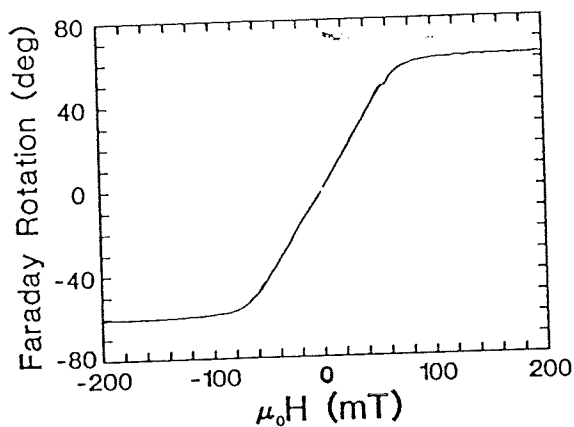


Figure 2. Magneto-optic response of pure YIG sample 3 mm long and 5 mm in diameter.

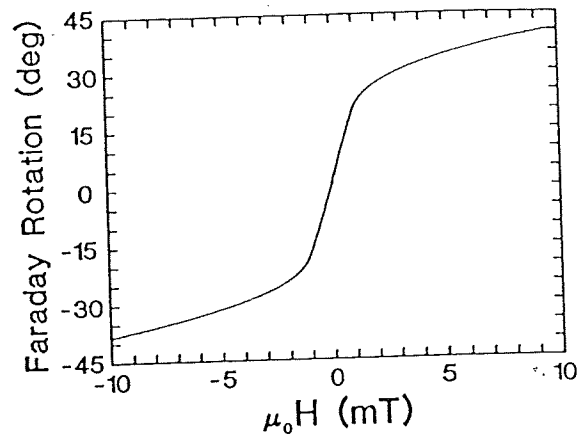


Figure 3. Magneto-optic response of Ga:YIG sample 3 mm long and 1 mm in diameter.

The measured dependence of Faraday rotation on the applied magnetic field (at room temperature) for the two samples is compared in Figs. 2 and 3. Both samples exhibit well-defined linear regions with negligible hysteresis. The sensitivity of the pure YIG sample is approximately 0.7 deg/mT while that of the Ga:YIG sample is approximately 18 deg/mT, or about 26 times greater. After we account for the different demagnetization factors, we find that the sensitivity of the Ga:YIG composition is about 5.9 times greater than of pure YIG. This is somewhat larger than the estimated factor of 4.3 calculated above from published values of e_F^{sat} and M_{sat} . Another difference between the data of Figs. 2 and 3 is the nature of the transition from the linear response toward saturation. While the YIG sample exhibits nearly zero slope above the knee of its response curve, the Ga:YIG sample appears to saturate much more slowly. This indicates that, unlike the YIG sample, the sensitivity of the Ga:YIG sample apparently can not be accurately estimated from saturation values of the magnetization and Faraday rotation. We do not know whether this effect is due to the different compositions, different geometries, or both.

The temperature dependence of the sensitivity of the Ga:YIG sample was also measured. This was done by fitting a line to data of rotation versus applied field measured at discrete temperatures between 25 and 115°C. In order to compare the temperature dependence of the sensitivity of Ga:YIG with that of YIG, as measured by Kamada et al.,² the data were normalized to the room-temperature sensitivity. These data, shown in Fig. 4, show that the sensitivity of the Ga:YIG sample is substantially less temperature dependent than is pure YIG.

The minimum detectable (or noise-equivalent) magnetic field for the gallium-substituted YIG sample was measured by connecting the output of a differential detection system to a signal analyzer. A 500 Hz magnetic field was applied to the sample by Helmholtz coils driven by an audio amplifier.

The magnitude of the applied field, $\mu_0 H$, was approximately 10^{-7} T. The measured signal and noise spectra, measured in a noise bandwidth of 0.187 Hz, are shown in Fig. 5. The noise-equivalent field at 500 Hz is approximately $100 \text{ pT}/\sqrt{\text{Hz}}$.

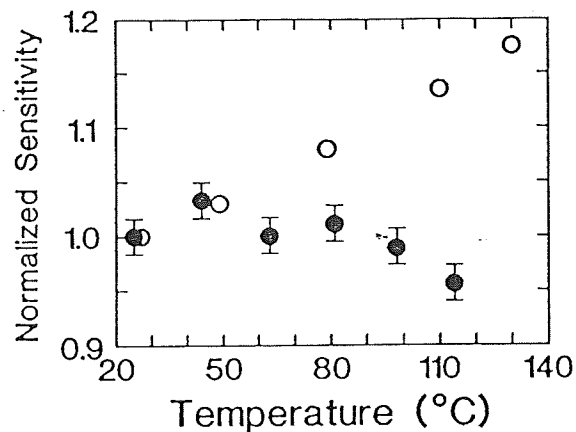


Figure 4. Sensitivity of pure YIG (open circles) compared to Ga:YIG (filled circles) normalized to room-temperature values. YIG data from Kamada, et al.²

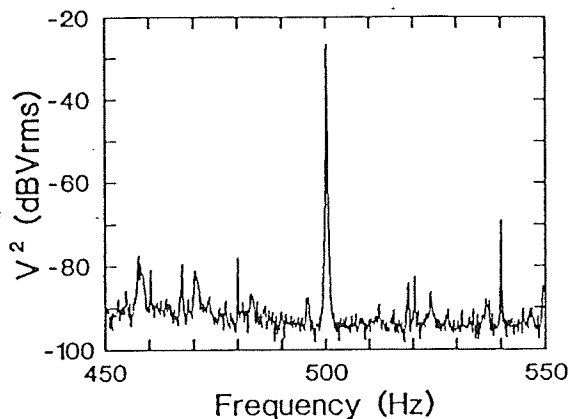


Figure 5. Spectral noise data obtained with Ga:YIG sample exposed to 10^{-7} T rms, 500 Hz, magnetic field. The noise-equivalent magnetic field is approximately $100 \text{ pT}/\sqrt{\text{Hz}}$.

6. CONCLUSION

Ferrimagnetic iron garnets offer much greater sensitivity than other materials used as sensing elements in Faraday-effect magnetic field sensors. Furthermore, diamagnetic substitution in certain garnets allows control over the magnetic properties which can increase sensitivity even further. The composition $\text{Y}_3\text{Ga}_{1.0}\text{Fe}_{4.0}\text{O}_{12}$ exhibits sensitivity about 6 times greater than the sensitivity of pure YIG at $1.3 \mu\text{m}$. The increased sensitivity is a consequence of the fact that the gallium substitution reduces the saturation magnetization much more than the Faraday rotation. The same composition also appears to be significantly less temperature sensitive. The minimum detectable field of a Ga:YIG sample 1 mm in diameter and 3 mm long was measured as approximately $100 \text{ pT}/\sqrt{\text{Hz}}$.

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13. Demagnetization factors were calculated according to the equivalent-ellipsoid approximation. See, for example, D. J. Craik, *Structure and Properties of Magnetic Materials* (Pion Limited, London, 1971) p. 22.
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