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NEWSPAPER

High frequency magnetic field sensors based on the Faraday effect in garnet thick films

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The Faraday effect in the thick epitaxial films of magnetic garnets of the type used in magneto-optic isolators can be used as the basis for a fiber-optic magnetic field sensor. These films have uniaxial anisotropy perpendicular to the surface and they contain bismuth to enhance the Faraday rotation. The typical magnetic domain pattern of meandering stripes changes in response to an applied field perpendicular to the film and this changes the polarization of infrared light propagating perpendicular to the film. Theory and experiment show that the speed of operation is limited by relaxation or resonance effects to upper frequencies between 10^6 and 10^9 Hz. Maximum sensitivity requires low magnetic moment and large thickness, in conflict with the requirements for high speed.

The Faraday effect in ferrimagnetic garnets can be used as the basis for fiber optic magnetic field sensors.^{1,2} Single crystals of substituted yttrium iron garnet (YIG) can be in bulk form, or epitaxial thin films with planar anisotropy,³ or thick films with uniaxial anisotropy perpendicular to the surface.⁴ The growth of magnetic domains parallel to the applied field at the expense of antiparallel domains results in changing Faraday rotation of the plane of polarization of transmitted infrared light. In this letter, we report on the sensitivity and speed of sensors based on thick uniaxial garnet films, with the applied field and the light propagation direction perpendicular to the film. In zero field, these films have up and down magnetic domains of equal area, forming the familiar stripe pattern shown by their Faraday rotation in Fig. 1. The changes in this pattern with magnetic field determine the sensitivity and limit the maximum operating speed of a magnetic field sensor.

For thick films, the magnetization increases linearly with field and it saturates (i.e., all of the stripe domains are wiped out) in a field that is approximately equal to the strength of the saturation magnetization M_s . When linearly polarized light is used to probe a large number of stripe domains, with an analyzer set at 45° to the input polarization direction, the transmitted intensity also varies linearly with field for small rotation angles. The sensitivity is therefore inversely proportional to the magnetization and linearly proportional to the film thickness times the Faraday rotation constant.⁵

The high frequency behavior of this field sensor depends on domain wall damping or domain wall resonance in the same way as the magnetic susceptibility. The standard theory of the susceptibility of thick uniaxial films^{6,7} begins with the equation of motion for small displacements x of the domain walls (in SI units)

$$m\ddot{x} + \beta\dot{x} + \kappa x = 2\mu_0 H M_s, \quad (1)$$

where m is the effective mass of the domain walls per unit area:

$$m = \frac{2}{\mu_0 \gamma^2} \left[\frac{K}{A} \right]^{1/2}, \quad (2)$$

β is the viscous damping coefficient:

$$\beta = \frac{2M_s}{\gamma} \left[\frac{K}{A} \right]^{1/2} \alpha, \quad (3)$$

and κ is the wall stiffness coefficient, related to the demagnetizing field.

$$\kappa = \left[\frac{\mu_0}{4\pi} \right]^{3/2} \frac{(1.7)^{3/2} M_s^3}{[(AK)^{1/2} L]^{1/2}}. \quad (4)$$

In these expressions, A is the exchange energy, K is the uniaxial anisotropy energy, γ is the gyromagnetic ratio, $= 1.76 \times 10^{11}$ rad/s T, M_s is the saturation magnetization, H is the applied field perpendicular to the film, α is the damping constant (proportional to the ferromagnetic resonance linewidth), and L is the film thickness. Equation (4) is an approximation that ignores the domain complexity discussed below, and the finite thickness to domain width ratio.



FIG. 1. Stripe domain pattern in film 2 revealed by Faraday rotation of the up and down domains. The stripes are $12 \mu\text{m}$ wide. Similar stripes in film 1 are $7 \mu\text{m}$ wide.

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TABLE . Properties of garnet thick films.

	Film 1	Film 2	Film 3
Composition	(BiY) ₃ Fe ₃ O ₁₂	(BiTb) ₃ (FeGa) ₅ O ₁₂	(BiTb) ₃ (FeGa) ₅ O ₁₂
Film thickness (μm)	60 \times 2	100 \times 2	320
A (J/m)	3.7 \times 10 ⁻¹²	3.0 \times 10 ⁻¹²	2.5 \times 10 ⁻¹²
M _s (kA/m)	143	56	28
K (J/m ³)	1.4 \times 10 ⁴	4.5 \times 10 ³	4.7 \times 10 ³
Stripe width	7 μm	12 μm	50 μm
Damping	Low	High	High
Faraday rotation at 1.3 μm	27°	27°	45°

Solving Eq. (1) assuming a sinusoidally varying applied field with radial frequency ω gives for the real part of the susceptibility χ ($= M/H$) divided by its low frequency value:

$$\chi/\chi_0 = \frac{\kappa(\kappa - m\omega^2)}{(\kappa - m\omega^2)^2 + \omega^2\beta^2} \quad (5)$$

If the damping is very small, the susceptibility at high frequencies shows a resonant behavior (domain wall resonance) at a frequency given by $(\kappa - m\omega^2) = 0$. If the damping is large, then χ shows relaxation behavior: a constant value at low frequencies, falling to one-half of this value at a frequency of κ/β , and then dropping off as $1/\omega^2$ at high frequencies. (See Fig. 4.) Note that

$$\kappa/\beta \propto M_s^2 / (K^{3/4} L^{1/2} \alpha) \quad (6)$$

In this study, three thick films grown for magneto-optic isolator experiments were studied. They all contained bismuth to enhance the Faraday rotation and were grown by standard liquid phase epitaxy (LPE) techniques on Ca-Mg-Zr substituted gadolinium gallium garnet (111)-oriented substrates. Films 1 and 2 are double films grown on both sides of the substrate. Film 3 is a free-standing film with the substrate removed. The relevant properties of these films are listed in Table I. The saturation magnetizations and uniaxial anisotropy energies were measured with a vibrating sample magnetometer. The exchange energies were estimated from the known values for the pure garnets, and the expected drop due to dilution of the iron with gallium.⁸ The stripe widths were measured by observing the Faraday rotation of the domains at near infrared wavelengths where the garnets are transparent and the video camera still has some sensitivity. The stripes in film 2 are shown in Fig. 1. Film 1 appears similar. In film 3 the domains are much wider and more complex, as shown in Fig. 2. On one surface, the stripe domains have undulations with a period similar to the stripe width [Fig. 2(a)]. As the focus is moved to the middle of the film, these undulations disappear. On the other surface they reappear, not correlated with the first surface, and small spike domains of reverse magnetization appear. This complex domain structure is associated with surface demagnetizing effects, and is typical of very thick films.⁹

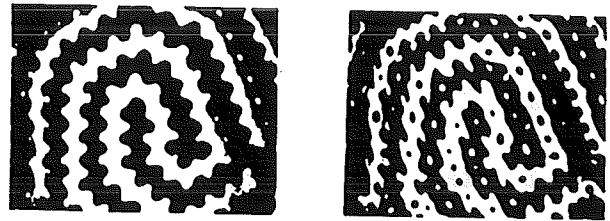


FIG. 2. Complex domain pattern of film 3. (a) Undulations in the stripes near one surface. (b) Undulations and reverse spike domains near the other surface.

To measure the optical sensitivity, 1.31 μm linearly polarized light was collimated into a 0.5 mm beam, passed through the film, and a 45° analyzer and was detected with a germanium detector. With 50 Hz magnetic fields applied perpendicular to the film, the response was linear and the coercivity was less than 10 A/m for fields up to at least half the saturation field in each case. The sensitivities of films 1, 2, and 3 were in the ratio 1:2:7, close to the measured ratios of the Faraday rotation divided by the magnetization.

The high frequency response measurements were performed with a frequency synthesizer, a rf amplifier, and a dielectric-filled coaxial transmission line that generated the rf magnetic fields. The coaxial structure contained a slot that held the sample in place near the center conductor, and transversely oriented holes that provided an unobstructed path to the sample for the collimated output of a 1.32 μm solid state laser. The calculated amplitude of the rf magnetic field at the sample varied from 5 to 15 A/m. When tested with a network analyzer, the rf transmission of this system without a sample showed no resonances up to 5 GHz. As shown in Fig. 3, the response for film 1 rose to a resonant peak at 6×10^8 Hz. (Note: the apparent gentle rise at lower frequencies is believed to be an artifact related to the characteristics of the rf amplifier or the coaxial transmission line.) Films 2 and 3 exhibit the relaxation behavior expected for these high loss films, as shown

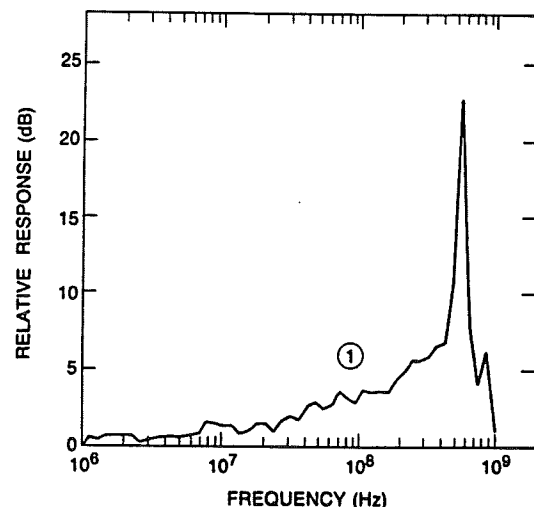


FIG. 3. Optical response vs frequency of the applied field for film 1 showing resonance behavior.

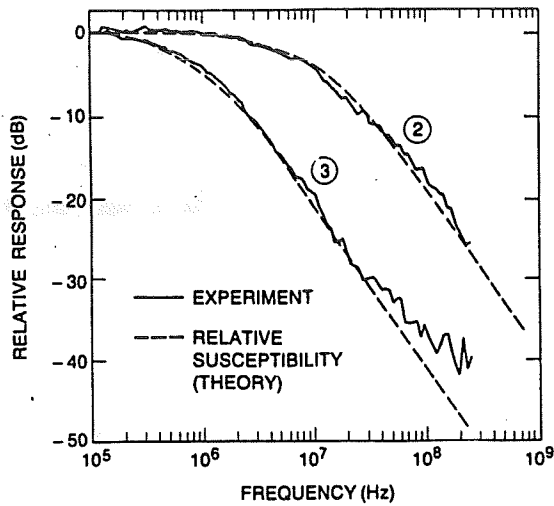


FIG. 4. Optical response vs frequency of applied field for films 2 and 3 showing relaxation behavior. The dashed line is the theoretical susceptibility vs frequency, fitted by adjusting the loss parameter of each film.

in Fig. 4. The 3 dB roll-off frequencies are 8×10^6 and 7×10^5 Hz.

For the low loss film 1, the theoretical value for the resonant frequency, Eq. (5) is 1.6×10^8 Hz. This is in reasonable agreement with the measured value. For the high loss materials, the excellent agreement between susceptibility theory and optical response experiments shown in Fig. 4 was obtained by setting the one adjustable parameter, α , to 0.09 for film 2 and 0.14 for film 3. These values are not unreasonable for films that contain sizable amounts of very lossy terbium ions.

In conclusion, the frequency response of magnetic field sensors based on uniaxial garnet thick films can be at least qualitatively understood in terms of the theory of magnetic susceptibility. In the presence of domain walls, higher wall resonance or relaxation roll-off frequencies can be obtained by maximizing the magnetization of the material and minimizing the film thickness, the uniaxial anisotropy and the damping. [See Eq. (6).] If rare earth ions are added to the garnet composition, terbium is the worst choice because it has the largest damping, although it is the best choice for temperature dependence. The sensitivity of these field sensors can be optimized by decreasing the magnetization (as long as the corresponding coercivity and domain size are not too large) and increasing the thickness for greater Faraday rotation. Since these requirements conflict with those for high speed, a compromise must be reached for each potential application.

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