Detection of weak (∼0.5–300 nT), low frequency (5–100 Hz) magnetic fields at room temperature by kilohertz modulation of the magneto-optical hysteresis in rare earth–iron garnet films

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Periodic magnetic fields with frequencies in the 5–100 Hz range and peak strengths as low as 0.5 nT have been detected at 300 K by modulating at kHz rates the magneto-optical response of epitaxial (Tm,Bi)5(Ga,Fe)3O12 rare earth–iron garnet films at λ = 532 nm. By exploiting the −1°/μT slope of the magneto-optical transition region between the two magnetization states of these low coercivity (<0.5 mT) films, sub-nT field strengths can be measured by upconverting the detection process into the kHz domain. The domain wall velocities are measured to be 3–30 m/s for modulation frequencies in the 0.3–10 kHz interval, and the noise generated by wall motion appears to be the primary barrier to further reductions in the detection sensitivity floor. Films with thicknesses of 2–4 μm and mean domain widths of 3–6 mm exhibit figures of merit (Θ/α) of ∼3°–8.5° at 532 nm. Imaging of mesoscopic magnetic particles is demonstrated with a spatial resolution of <300 μm. © 2007 American Institute of Physics. [DOI: 10.1063/1.2713144]

Detection and imaging of electromagnetic fields have long been of fundamental interest in physics and the engineering sciences owing to its ability to probe functioning systems noninvasively. Magnetoencephalography, for example, provide functional imaging of the human heart and brain, respectively, and are generally based on the spatially-resolved detection of magnetic fields by superconducting-quantum-interference-device (SQUID) based systems having a field strength sensitivity floor of <100 pT (Refs. 1 and 2). Produced by bioelectric currents or artificial fields generated by magnetic nanoparticles introduced to the body, biomagnetism provides an access to critical clinical data such as evoked brain responses and the location and extent of injured myocardial tissue. The Faraday effect offers an alternative avenue to the remote measurement of magnetic fields, and has been applied to subsurface crack detection in aircraft as well as nondestructive evaluation of integrated circuits.4 However, Faraday effect magnetic sensors have generally been confined to the measurement of field strengths on the order of millitesla. By employing flux concentrators, Deeter et al.5 demonstrated the detection, with an iron garnet crystal, of sinusoidal fields as weak as 470 pT (rms) but the lower bound on the frequency of the test field was 500 Hz–1 kHz.

This letter reports the detection at room temperature of low frequency (5–100 Hz) magnetic fields with peak strengths as low as ∼0.5 nT by modulating the magneto-optical response of rare earth–iron garnet films in the 0.3–20 kHz range. In the transition region between the two stable magnetization states of these low coercivity (<0.5 mT) films, the response is characterized by hysteresis and a steep slope (∼−1°/μT) which together enable the minimum detectable field strength to be reduced to <1 nT.

Several rare earth–iron garnet (RIG) films, grown on ∼7.5 cm (3 in.) diameter gallium gadolinium garnet (GGG) substrates and having the nominal composition (Tm,Bi)5(Ga,Fe)3O12 were acquired from a commercial source (Litton Airtron) and analyzed both optically and by surface and bulk analytical diagnostics. Examination of these epitaxial films by energy dispersive x-ray spectroscopy (EDS) shows the stoichiometry to be (Tm,Bi,Fe,Pb)x ×(Ga,Fe)3O12 where 2.38 ≤ x ≤ 2.45, 0.65 ≤ y ≤ 0.73, 0.04 ≤ z ≤ 0.09, 1.13 ≤ a ≤ 1.27, and 3.55 ≤ b ≤ 3.66. The experimental results described here focus on a subset of the films that are rich in Ga (a ≥ 1.22).

Measurements of the magneto-optical response for five films are summarized in Fig. 1(a). The ordinate of Fig. 1 is the figure of merit Θ/α, where ΘF and α are the Faraday rotation angle and film absorption coefficient, respectively. The letter associated with each of the film responses illustrated in Fig. 1(a) is for identification purposes only. Film thicknesses, measured by both electron microscopy and laser interferometry, ranged from 2 to 4 μm, and all of the data presented here were obtained for a laser wavelength of λ = 532 nm. Hysteresis is evident for all of the films investigated and, in each case, the coercivity is <0.5 mT. Most of the films represented in panel (a) of Fig. 1 are characterized by a steep transition region between the two stable magnetization states in which |ΘF/α| ranges from ∼3° to 8.5°. In this transition region, slope values are typically on the order of 1°/μT, or roughly three orders of magnitude larger than that for the linear response of bulk iron garnet crystals, which suggests the magnetic field detection scheme illustrated qualitatively in Fig. 1(b). Specifically, upon applying an external sinusoidal modulation field of the proper magnitude and frequency (typically 0.3–20 kHz), the response of the film will follow the pathway indicated by the red closed loop. When the weak magnetic field to be measured (test field) is then introduced, the operating region is defined by the blue trace of Fig. 1(b). The wave forms at lower right of the figure are those corresponding to these two regions of operation (i.e., with and without the test field) and show the temporal variation of the Faraday rotation angle. It is evident that the addition of the test field alters the signal wave form.

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in two respects, one of which is to shift the dc level. Both synchronous detection or dc shift measurements rely on the modulation of the magneto-optical response to, in effect, up-convert the detection process into the kHz domain, thereby measuring the strength of a low frequency (<100 Hz) magnetic field while minimizing the 1/f noise from which direct detection suffers. For the sake of brevity, the results described here were obtained with the latter experimental approach. It should also be mentioned that, owing to reliance on the intrinsic nonlinearity of the transition region of the film’s response, carefully characterizing the response profile itself and determining the dynamic range are critical to realizing the maximum sensitivity of both approaches to magnetic field detection and ensuring measurement reproducibility.

Before presenting the field measurement sensitivity data, several comments are in order regarding the domain structure of the films investigated. Returning to Fig. 1(a), note that the magneto-optical response for one of the films (e) differs considerably from the others. Analysis of this film (and others with a similar response characteristic) by EDS, as well as electron and optical microscopy, reveals that the response of film e is representative of that for films having a serpentine domain structure which is generally associated with growth-induced anisotropy in epitaxial iron garnet films. The remaining films in Fig. 1(a), the focus of these experiments, were found to have much larger domains that are characteristic of rare earth–iron garnet films that have been annealed with the intent of reducing the growth-induced anisotropy. Analysis of microscope images with the two-dimensional fast Fourier transform shows that the mean domain widths (along both orthogonal coordinates in the plane of the domains) lie in the 0.2–0.45 mm range for the serpentine (annealed) domain films as opposed to mean widths of ~3–6 mm for the domains of films a–d.

Because the magnetic domains in (Tm,Bi)3(Ga,Fe)4O12 films change magnetization states by domain wall motion, the domain wall velocity determines the minimum switching time for a given domain and, therefore, the maximum modulation frequency for these experiments. Consequently, the domain wall velocities for the films of Fig. 1 were estimated by applying a variable frequency modulation field with an amplitude of 1 mT (thus exceeding the coercivity of all of the films) and measuring the slope of the magneto-optical response at the midpoint of the transition between magnetization states. From averages taken over 100 measurements and the mean domain widths mentioned earlier, the minimum domain switching time and mean domain wall velocity were determined, and the saturation velocities are in the range of 3–30 m/s, which agrees well with values reported previously for other iron garnets.

Figure 2 is a schematic diagram of the experimental arrangement incorporating a polarimeter in which the frequency-doubled output of a diode-pumped Nd: YVO₄ laser is linearly polarized by a polarizer with an extinction ratio of 5 × 10⁸:1, transmitted by the RIG film, and then incident on a second polarizer, oriented at a 45° angle relative to that of the first polarizer. The second polarizer splits the beam into two components, both of which are detected and subtracted by a balanced receiver. A pair of coils supplies the modulation magnetic field which determines the operating region for the RIG film, and the bias coil applies a secondary field to counteract any tendency of the film to remain in one of the two magnetization states.

The balanced receiver was effective in lowering the rms noise level in the ≤1 kHz region by almost 20 dB and completely suppressed narrow bandwidth, laser intensity noise at several discrete frequencies between 105 and 943 Hz. A cylindrical shield comprising four layers of μ-metal was designed and custom fabricated to suppress external magnetic fields in the <100 Hz range by at least five orders of magnitude. For a 95 nT, 100 Hz test field, for example, the magnetic shield was observed to lower the ambient noise floor.
uniformly over the \( \sim 40-200 \) Hz region and by \( \sim 30 \) dB relative to the test signal.

Data illustrating the minimum field strength detectable with the system of Fig. 2 are presented in Fig. 3 for three of the films of Fig. 1 and a test signal frequency, sampling window, and modulation frequency of 97 Hz, 100 s, and 20 kHz, respectively. The solid lines are least-squares fits to the data which demonstrate the excellent linearity of the detection system as a whole, and the RIG films specifically, over the entire 3–400 nT range. The dashed horizontal lines in Fig. 3 indicate the minimum detectable electrical signal for each of the three films. For all of the experiments conducted to date, the detection floor is \( \sim 1 \) nT. Increasing the sampling time (to as much as \( \sim 15 \) min) improves the system detection threshold only marginally (to \( \sim 0.5 \) nT).

Experiments conducted in the absence of a test field clearly demonstrate that the dominant source of noise at present originates from the films themselves. Generated only with the modulation field present, this noise is attributed to domain instability and wall motion and varies from film to film. Measurements of the rms noise produced over the 0–100 Hz interval by modulating fields in the \( \approx 20 \) kHz range show that domain instability produces as much as five times the noise generated by all other remaining sources.

Finally, we note that magnetic fields can also be imaged by replacing the photodetection scheme of Fig. 2 with a charge-coupled device (CCD) camera. Panel (a) of Fig. 4 is an image of the field distribution produced by two Sm:Co particles, each \( \sim 300 \) \( \mu \)m in diameter and separated by \( \sim 2.2 \) mm. A three-dimensional, false color rendering of the field and a lineout of the field distribution along the axis connecting the centers of the particles, are shown in parts (b) and (c) of Fig. 4, respectively. Clear images are produced with only 2 s of CCD integration time, and the spatial resolution is \( \approx 300 \) \( \mu \)m. It must be emphasized that, despite the large mean domain size (several mm), the incremental domain wall movement observed allows for imaging with a spatial resolution significantly less than the overall domain size.

In summary, the demonstration and characterization of a system capable of detecting magnetic fields as weak as \( \sim 0.5 \) nT have been described. By modulating at kHz rates the magneto-optical response of epitaxial RIG films and exploiting the \( \sim 1^\circ / \mu T \) slope of the transition region, weak magnetic fields can be detected and their spatial distribution measured. Hysteresis associated with these low coercivity films, previously regarded as an impediment to magnetic field detection, can now be viewed as an asset.

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