Wideband Current and Magnetic Field Sensors
Based on Iron Garnets

M.N. Deeter, K.B. Rochford, A.H. Rose, and G.W. Day
Electromagnetic Technology Division
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80303
PH (303)497-5400 FAX (303)497-3387

Sensors based on the Faraday effect can be configured to measure either magnetic fields or electric currents.[1] Such sensors can be constructed without introducing conducting materials which are often undesirable. Presently, the most sensitive Faraday effect sensors employ ferrimagnetic iron garnets as the sensing elements. With these materials, we have demonstrated minimum detectable fields as low as 1 $pT/Hz^{1/2}$ and currents as low as 200 $nA/Hz^{1/2}$. This paper reviews these and other recent research results obtained at NIST and considers prospects for still further improvements in sensitivity and frequency response.

Principles of Faraday Effect Sensors

Magnetic fields applied to some materials induce a circular birefringence proportional to the field component along the optical path. By introducing a linearly polarized optical beam into such a magneto-optic material, the Faraday effect causes a rotation θ_F of the plane of optical polarization; this rotation can be converted to an optical intensity by placing a polarizer after the material (see Fig. 1). For such a polarimetric system, the transmission is given by $T=\cos^2(\theta_F+\theta_0)$, where θ_0 is the relative angle between the transmission axes of the polarizers. For $\theta_0=45^\circ$, the transmission is linear in the small-signal limit of θ_F. Thus, this polarimetric system operates with the same transfer function as that of a Mach-Zehnder interferometric modulator and exhibits the same higher-order distortion performance. However, unlike interferometric modulators, the bias θ_0 is stable since it is fixed mechanically. This largely eliminates drift and the need for active tracking to reduce even-ordered harmonics.

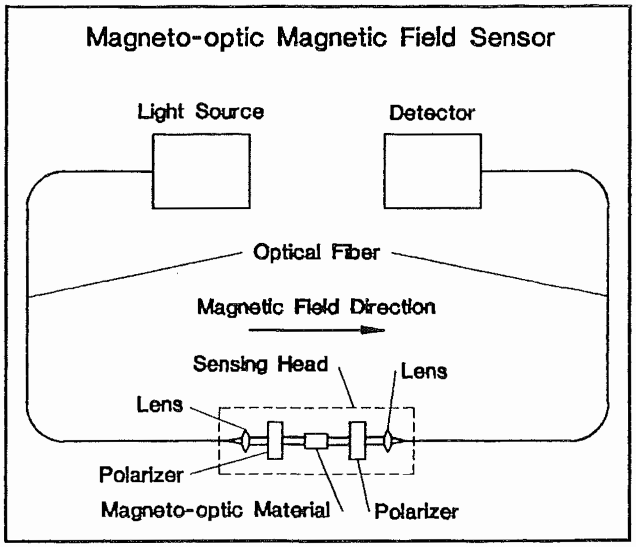

Figure 1. Magneto-optic magnetic field sensor.

With the exception of the optical source and detector, which can be remotely located with fiber-optic uplink and downlinks, the system is all-optical. In addition to the advantages of optical sensing (nonconductive components, immunity of links to electromagnetic interference, etc.), the large magneto-optic response of ferrimagnetic iron garnets provides excellent sensitivity.[2] These commercially available materials have been used to demonstrate both magnetic field and electric current sensors.

Characteristics of Iron Garnets

Iron garnets are ferrimagnetic materials that contain domains of permanent magnetic moments. In the demagnetized state, the domains' moments are arranged such that the net magnetic moment is zero. When an iron garnet is subjected to an applied magnetic field, the domains can respond in two different ways: domain wall motion and magnetization rotation. Both of these mechanisms produce a net magnetic moment in response to the applied magnetic field. At sufficiently high applied fields the magnetization saturates as all moments are aligned with the applied field. For applied magnetic fields H below the saturation value H_{sat}, the induced rotation is ideally given by

$$\theta_F = \theta_F^{sat} \frac{H}{H_{sat}}, \qquad (1)$$

where θ_F^{sat} is the saturation Faraday rotation for a given crystal. Though rotation for fields exceeding H_{sat} approaches an asymptotic limiting rotation θ_F^{sat}, the response is linear for $H < H_{sat}$. Hysteresis, which is associated with domain wall motion and which limits linearity, is minimized when the optical beam is much larger than the average domain. Total system linearity can then be limited by the sinusoidal transfer function for fields below saturation.

Yttrium iron garnet ($Y_3Fe_5O_{12}$, or YIG) is commercially available as bulk crystals. Gallium-substituted YIG ($Y_3Fe_4Ga_1O_{12}$, or Ga:YIG) exhibits a smaller H_{sat} than YIG, resulting in higher sensitivity.[3] For example, a YIG crystal 3 mm in length and 1 mm diameter exhibits a sensitivity of 6 °/mT. A Ga:YIG crystal with the same dimensions exhibits a three-fold increase in sensitivity, to 18 °/mT. This increase comes with a penalty however. The frequency response -3 dB point occurs at 700 MHz for YIG, but is significantly reduced to 6 MHz for Ga:YIG.

The sensitivity of YIG can also be increased by substituting ions which increase the saturation rotation θ_F^{sat}. Bismuth substitution, for example, can increase θ_F^{sat} by up to an order of magnitude. To date, this enhancement has been demonstrated only in garnet films, but prospects for bismuth substitution in bulk iron garnet crystals are good.

Magnetic Field Sensors

Iron garnets can be incorporated in magnetic field sensors using a simple polarimetric detection system (Fig. 1). The sensor element can be remotely located by using an optical fiber uplink that transmits linearly polarized light to the magneto-optic material through a polarization maintaining optical fiber, or by transmitting "depolarized" light through a standard optical fiber and repolarizing the light just before the iron garnet crystal. In the sensor head, collimating lenses are used to couple light from the uplink, through the active material, and into the downlink. The down link delivers optical power transmitted through the analyzing polarizer back to the detection system. Immunity from drifts in source power can be achieved by replacing the analyzer with a polarizing beamsplitter and detecting both output beams. The two signals are processed with an analog circuit that ratios the signal difference and the sum. The best recorded minimum detectable field for such a sensor is 100 pT/Hz$^{1/2}$ at 1 kHz and was achieved with a Ga:YIG crystal.

Recently, additional improvements have been observed with the addition of ferrite flux concentrators (Fig. 2). These devices are high-permeability elements that amplify the magnetic field within the magneto-optic material. The amplification is achieved through two complementary effects. First, the elements have large cross-sectional areas (A_C) that taper toward the smaller Faraday crystal (A_{MO}). The flux density (and therefore sensitivity) within the magneto-optic crystal is larger than in the flux concentrators by the ratio A_C/A_{MO}. Second, the demagnetization factor of the magneto-optic crystal is effectively decreased by the addition of the high-permeability material; this decreases the saturation field H_{sat}, leading to increased sensitivity in Eq. 1.

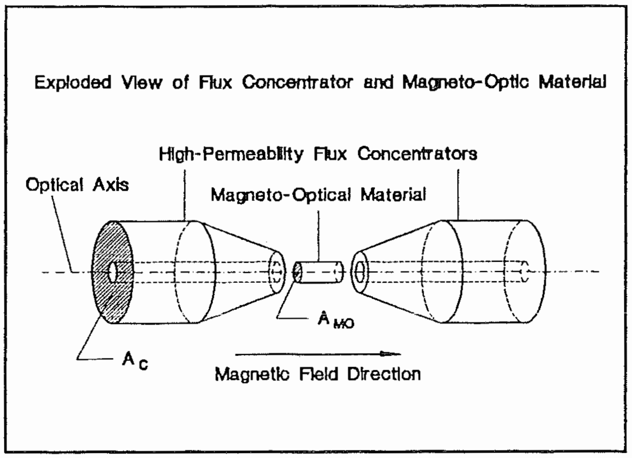

Figure 2. Magneto-optic sensor with flux concentrators.

The effect of the flux concentrators is exemplified in Fig. 3. A 46 dB increase in low frequency sensitivity is observed. The increase remains at higher frequencies, but with decreased gain. This is thought to be due to the limited frequency response of the particular ferrite used in this example and may be improved with other materials. The minimum detectable field of 1 pT/Hz$^{1/2}$ represents about a hundred-fold improvement in sensitivity and confirms the benefit of flux concentration.

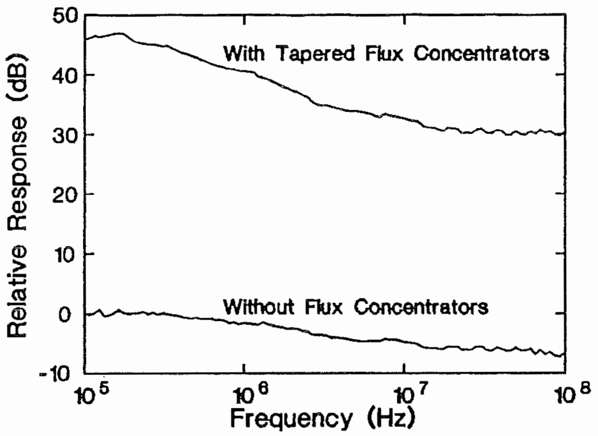

Figure 3. Frequency response of sensor with and without flux concentrator.

Electric Current Sensors

According to Ampere's law, the line integral of a magnetic field around a conductor is equal to the current carried by the conductor. Thus, if a conductor is encircled with magneto-optic material which forms a closed optical path, the resulting Faraday rotation will be proportional to the current and will be insensitive to other sources of magnetic fields. This is the basis for an optical current sensor.

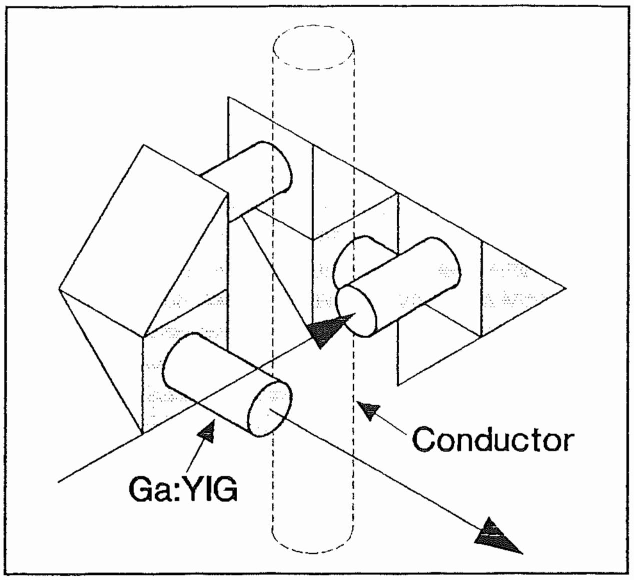

Figure 4. Optical Ga:YIG current sensor.

An example of a garnet-based current sensor is shown in Fig. 4. Four cylindrical Ga:YIG sensing elements measuring 5 mm in length and 1 mm diameter are connected by right-angle prisms to provide an optical path around the conductor. The prism pairs are used in complementary fashion so that the Fresnel reflection phase shift generated at the first reflection is exactly cancelled at the second reflection. If these phase shifts were not controlled, the sensitivity of the detection system could be reduced significantly. However, since the magneto-optic sensitivity of the glass prisms is negligible compared to the Ga:YIG sensitivity, the sensor does not evenly integrate the magnetic field over the closed optical path. Thus, the sensor is not totally immune to stray magnetic fields. Work is underway to minimize these gaps.

The measured sensitivity of this device is about 3 °/A; to achieve similar sensitivity with a device exploiting the Faraday effect in optical fiber would require more than 11 000 turns of optical fiber. The minimum detectable current for the present device is about 200 $nA/Hz^{1/2}$. The measured cutoff frequency was 4 MHz, and was limited by the Ga:YIG response. Greater bandwidths (>500 MHz) are available using pure YIG, but even the Ga:YIG sensor exhibits a sensitivity-bandwidth product about 10 times greater than devices based on optical fiber.

Radiation Exposure Data

In environments where ionizing radiation is present, conductive sensor elements are undesirable since radiation may induce currents in the conductors. To demonstrate the feasibility of optical sensors in these environments, several magneto-optic materials were subjected to 30 ns pulses of X-ray (1 MeV peak and 2 MeV endpoint continuum) and electron-beam (1-1.2 MeV peak, 2-2.2 MeV endpoint) radiation produced by a febetron source. Before, during, and after each irradiating pulse, the optical transmittance at 1.3 μm of each material was monitored to measure induced darkening. The measured results are tabulated below in Table 1.

Compared to ZnSe and CdMnTe, which also exhibit large magneto-optic effects, the iron garnets showed better resistance to radiation-induced changes. In fact, YIG and Ga:YIG exhibited induced changes of only 2 to 3 times greater than the changes observed for SiO_2, which is nominally considered radiation hard.

TABLE 1. RADIATION-INDUCED TRANSMITTANCE CHANGES

Sample	ΔT (%)	Total Dose, Gy (Si)
YIG	0	0.2-0.3 X-ray
Ga:YIG	0	0.2-0.3 X-ray
CdMnTe	-1.6	0.2 X-ray
SiO_2	0	0.2 X-ray
YIG	-4.9	0.3 e^--beam
Ga:YIG	-5.8	0.3 e^--beam
CdMnTe	-66.6	0.3 e^--beam
ZnSe	-100.0	0.3 e^--beam
YIG	-12.5	1.4 e^--beam
Ga:YIG	-18.	1.4 e^--beam
CdMnTe	-100	1.4 e^--beam
ZnSe	-100	1.4 e^--beam
SiO_2	-5.1	1.4 e^--beam

Note: 1 Gy = 100 rad

Garnet Waveguide Sensors

Iron garnet films up to 100 μm thick can be grown using liquid phase epitaxy (LPE). Compared to bulk growth techniques, this process allows greater control over composition. For example, certain sensitivity-enhancing dopants which are difficult to incorporate in bulk crystals can routinely be incorporated into LPE films. In an optical waveguide geometry, long path lengths, which also increases sensitivity, are feasible.

The magnetic domains in these films are naturally oriented with their magnetizations perpendicular to the surface. An applied perpendicular magnetic field induces domain wall motion; domains magnetized antiparallel to the field shrink while domains magnetized parallel to the field expand. In contrast, a field applied parallel ("in-plane") to the surface causes magnetization rotation; in this situation, the domain walls remain fixed while the magnetizations of both types of domains rotate towards the applied field. Figure 5 demonstrates one result of this distinction. The response when the field is applied perpendicular to the plane decreases with frequency as a consequence of the temporal response of domain wall motion. The in-plane response, which is limited by the response time of magnetization rotation, is much faster. In this geometry, which forms the basis of garnet waveguide sensors, the film exhibits a cutoff frequency in excess of 1 GHz.

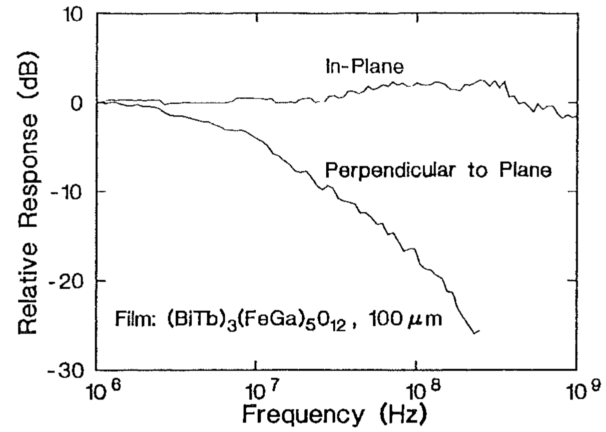

Figure 5. Frequency response of garnet film.

Conclusions

Optical sensors using bulk garnet crystals have been demonstrated with excellent results. A minimum detectable fields of 100 $pT/Hz^{1/2}$ was measured for a sensor based on Ga:YIG. When a flux concentrator was added, the minimum detectable field dropped to 1 $pT/Hz^{1/2}$. A current sensor constructed from four cylindrical bulk garnet elements and six right angle prisms exhibited a minimum detectable current of 200 $nA/Hz^{1/2}$. System bandwidths for iron garnet-based sensors are determined by garnet composition and shape, with cutoff frequencies as high as 700 MHz for pure YIG.

YIG crystals have been exposed to intense radiation pulses, and show darkening on the order of SiO_2. These findings indicate that iron garnets may be suitable for magnetic field and electric current sensors in ionizing radiation environments.

Finally, iron garnet films offer high-frequency operation beyond that observed in bulk garnets. The possibility of higher sensitivity and fabrication flexibility make these films a promising candidate for improved sensor response.

Acknowledgements

This work is sponsored in part by the Defense Nuclear Agency under DNA IACRO #92-830, and work units 00102. This paper represents work of the U. S. Government and is not subject to copyright.

References

[1] G. W. Day and A. H. Rose, "Faraday effect sensors: The state of the art," in *Proc. SPIE*, vol. 985, p. 138, 1989; also G. W. Day, M. N. Deeter, and A. H. Rose, "Faraday effect sensors: a review of recent progress," in *Advances in Optical Fiber Sensors*, B. Culshaw, E. L. Moore, and Z. Zhipeng, Eds., Bellingham, Washington: SPIE, 1992, pp. 11-26.

[2] M. N. Deeter, A. H. Rose, and G. W. Day, "Fast, sensitive magnetic-field sensors based on the Faraday effect in YIG," *J. Lightwave Tech.*, vol. 8, p. 1838, 1990.

[3] M. N. Deeter, A. H. Rose, G. W. Day, and S. Samuelson, "Sensitivity limits to ferrimagnetic Faraday effect magnetic field sensors," *Appl. Phys. Lett.*, vol. 70, p. 6407, 1991.