High Sensitivity Fiber-Optic Magnetic Field Sensors Based on Iron Garnets

Merritt N. Deeter

Abstract— **Ferrimagnetic iron garnet crystals form the basis of magnetooptic magnetic field sensors which offer high sensitivity, broad-band frequency response, and compatibility with fiber optics. Recent developments at NIST promise still greater performance for these devices in the near term. Specifically, new designs for magnetic field sensors, electric current sensors, and novel experimental iron garnet compositions demonstrate the potential for significantly improving the performance of these devices.**

I. Introduction

IRON garnet crystals have received steadily increasing interest in recent years as sensing elements in magnetoopticptic magnetic field sensors. Specialized magnetic field sensors, such as electric current sensors and rotation sensors have also benefitted from the use of garnets. Compared to conventional diamagnetic and paramagnetic magnetooptic materials, iron garnets offer much greater magnetooptic sensitivity, and therefore are capable of measuring much smaller magnetic fields. Unlike most conventional magnetic field sensors, iron garnets offer broadband (up to 1 GHz) frequency response. Moreover, the compatibility of iron garnets with fiber-optic systems makes these devices less prone to problems, such as electromagnetic interference, which can occur with conventional electrically-sensed devices. This paper reviews recent developments in the areas of both device and materials research, which seem likely to advance the capabilities of these sensors even further.

II. Device Development

A. Magnetic Field Sensors

The basic operating principles of Faraday effect sensors, and specifically iron garnet-based magnetic field sensors, have been described in detail elsewhere [1]–[3]. Most of these devices rely on polarimetric detection systems, which convert magnetic field-induced changes in polarization state into relative changes in optical intensity and then into electrical signals.

For magnetic field sensing, the magnetooptic sensitivity S (defined as the Faraday rotation per unit magnetic field) of bulk garnet crystals is given by

$$S = \frac{\theta_{F,\,\mathrm{sat}}}{N_D M_{\mathrm{sat}}} \tag{1}$$

where $\theta_{F,\,\mathrm{sat}}$ is the material's saturation Faraday rotation, M_{sat} is the crystal's saturation magnetization, and N_D is the demagnetization factor. Whereas N_D depends only on the crystal's length-to-diameter ratio [3], values of $\theta_{F,\,\mathrm{sat}}$ and M_{sat} vary widely with the garnet composition and temperature. In addition, both $\theta_{F,\,\mathrm{sat}}$ and optical absorption depend strongly on wavelength.

A simple technique that has been shown to dramatically increase the magnetooptic sensitivity of bulk iron garnet crystals exploits flux concentrators [4]. An exploded view of a sensor employing flux concentrators is shown in Fig. 1. The flux-concentrating elements are high permeability cylindrical bodies with cross-sectional areas much greater than that of the iron garnet crystal. Magnetic flux captured by the concentrators is constricted through the iron garnet crystal resulting in a large enhancement of the magnetic flux density. The flux concentrators also modify the iron garnet crystal's effective demagnetization factor. A sensitivity enhancement of 200 times was achieved when two conically-tapered ferrite cylinders were positioned coaxially at the two ends of a YIG crystal 1 mm in diameter and 3 mm long. The overall dimensions of the sensor were about 13 mm in diameter and 52 mm in length. The same device demonstrated a minimum-detectable magnetic field of 1.4 pT/$\sqrt{\ }$ Hz at 1 kHz.

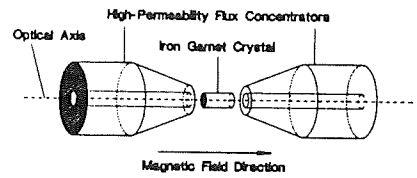

Fig. 1. Exploded view of magnetooptic magnetic field sensor based on iron garnet crystal and dual flux concentrators.

B. Electric Current Sensors

An optical current sensor is formed when a magnetooptic material forms a closed optical path around a current-carrying conductor [1]. By Ampére's law, the path-integrated magnetic field for such an optical circuit (which determines the net Faraday rotation) is proportional to the current in the conductor and is independent of magnetic fields generated by all other

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The author is with the Optoelectronics Div., National Institute of Standards and Technology, Boulder, CO 80303 USA.
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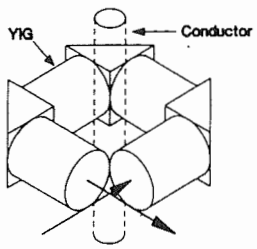

Fig. 2. Iron garnet current sensor employing prisms with nonphase-shifting multilayer coatings.

sources. Thus, a measurement of the net Faraday rotation in this configuration provides a measurement of the current in the conductor without sensitivity to spurious magnetic fields. Previously, this concept was successfully implemented in annealed coils of optical fiber [5].

Two generations of garnet-based electric current sensors employing this same principle have been developed recently at NIST [6], [7]. Both designs exploit total internal reflection from the hypotenuses of right-angle prisms as a method for defining the closed optical path. A significant design challenge posed by these devices is the nonzero phase shift generally produced by total internal reflection. Such phase shifts generally convert linearly-polarized light to elliptical polarization, which can seriously degrade performance. In the first-generation device [6], this phase shift was cancelled by the use of complementary prism pairs at each corner of the sensor. Since the s- and p-polarized electric field components are opposite for the two prisms, the net phase shift from each pair is zero. This device, which employed four gallium-substituted yttrium iron garnet (Ga:YIG) crystals (each measuring 5 mm in length and 1.5 mm in diameter) for the sensing elements, demonstrated a minimum detectable current of 220 nA/$\sqrt{}$ Hz and a -3 dB cutoff frequency of about 2.6 MHz.

A significant problem encountered with the complementary prism-pair design was the difficulty associated with the assembly and alignment tasks. In the second-generation device [7], shown in Fig. 2, specially designed non-phase-shifting multilayer coatings were applied to the prism hypotenuses. Not only was this sensor much easier to assemble and align than the first device, but it was also more compact. This sensor, which employed YIG cylinders each 2.5 mm long and 2 mm in diameter, demonstrated a minimum detectable current of 840 nA/$\sqrt{}$ Hz at 1.8 kHz and a -3 dB cutoff frequency of 500 MHz. The larger minimum detectable current of this device (relative to the first-generation device) was mainly a result of the use of YIG crystals (rather than gallium-substituted YIG) with shorter path lengths and larger demagnetization factors. On the other hand, the use of YIG also produced a sensor with a much higher bandwidth.

An implicit assumption made when invoking Ampère's law as a model for these current sensors is that the closed optical path is characterized by uniform magnetooptic sensitivity. Whereas this assumption seems quite valid for annealed coils of optical fiber, it is less valid when the circuit is composed of both magnetooptically sensitive elements (iron garnet crystals) and magnetooptically insensitive elements (such as prisms). An apparent result of this implicit approximation is that garnet-based current sensors are more susceptible to external sources of magnetic fields than are annealed coils of optical fiber. For example, whereas annealed fiber coils typically exhibit isolation values of approximately 55 dB [5], a worst-case value of only 10 dB was measured for the coated prism device for currents just outside the sensor [7].

C. Rotation Sensors

Recently, iron garnet crystals have also been widely investigated as magnetic field sensing components in rotation sensing devices [8]–[10]. Typically, these sensors rely on a ferromagnetic-toothed wheel attached to some rotating element. A magnetic field sensor positioned near the wheel's magnetized teeth (but not attached to the wheel itself) produces a repetitive magnetooptic signal as the wheel rotates. Measurement of the frequency of this signal provides a direct measurement of the wheel's rotation speed.

Iron garnets have been exploited for this application in two different configurations. The conventional Faraday configuration relies on polarizers that convert Faraday rotation generated in either a garnet film or bulk crystal to a change in optical intensity [8], [9]. A more sophisticated device exploits domain diffraction created by perpendicularly magnetized domains in garnet films [10]. When exposed to a collimated beam of light, the magnetic domain pattern in some garnet films gives rise to a diffraction pattern consisting of an undeviated zeroth-order beam in addition to a series of higher-order diffraction rings. The distribution of light among these orders is very sensitive to the net magnetization of the film [10], [11]. If, for example, only the zeroth-order beam is detected (for example, by spatially filtering the higher orders), a signal containing a term proportional to the square of the net magnetization results. As the fringing fields from the moving magnetized teeth modulate the film's magnetization, an optical signal indicative of the wheel's rotation speed is generated. This diffraction-based concept works equally well with polarized and unpolarized light and therefore requires no polarizers.

III. Iron Garnet Materials

A. Epitaxial Films

Magnetic field sensors based on iron garnet films have several potential advantages over sensors based on bulk crystals. For equal path lengths, films often exhibit much larger values of $\theta_{F,\mathrm{sat}}$, since they can usually be grown with larger amounts of compositional substituents, such as bismuth. Films can be exploited in either of two geometries. In the perpendicular geometry, the directions of the magnetic field and the light propagation are perpendicular to the film's surface. This geometry was described above as the basis of the diffraction-based rotation sensor. When combined with a differential detection system, this geometry offers a fundamentally linear magnetooptic response (within the limits of saturation), as opposed to most other polarimetric sensors that exhibit sinusoidal magnetooptic responses [11], [12]. On the other hand, values of $\theta_{F,\mathrm{sat}}$ for this geometry are limited by the

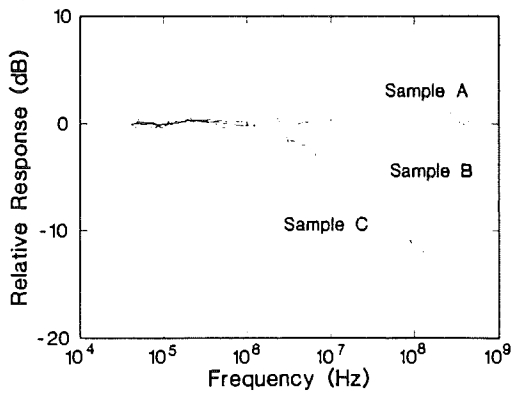

Fig. 3. Normalized frequency response data of novel iron garnet compositions.

TABLE I
MAGNETOOPTIC SENSING PARAMETERS OF NOVEL IRON GARNET COMPOSITIONS

	$\theta_{F,sat}/L$ (°/mm)	S' (°/A)	Freq. Resp.
YIG[a]	22	0.14	excellent
Ga:YIG[b]	14	0.6	poor
Sample A	106	0.8	excellent
Sample B	114	3.3	good
Sample C	32	12.6	poor

[a] from Ref. 17
[b] from Ref. 18

film thickness, which is generally less than several hundred micrometers. This disadvantage can be partially offset by using optical sources emitting at near-infrared wavelengths (700–900 nm), for which the saturation rotation is typically greater than at longer wavelengths, and the total absorption is limited because of the short path length [9], [10]. Such sources are not usually practical when the path length in the iron garnet exceeds several micrometers because of the strong absorption typical of iron garnets for wavelengths less than about 1000 nm. The frequency response associated with the perpendicular geometry is controlled by domain wall characteristics and for some compositions is virtually flat up to hundreds of megahertz [13].

Films with perpendicularly-magnetized domains are also well suited to sensors based on the optical waveguide geometry [14], [15]. In this configuration, light propagates within the plane of the film. As with all sensors based on the Faraday effect, the Faraday rotation results only from the magnetic field component parallel to the light's propagation direction. However, whereas the sensitivity of bulk iron garnet crystals is determined by demagnetization fields, the sensitivity of films in the optical waveguide geometry is governed by growth-induced magnetic anisotropy energy. An obvious advantage of this geometry over the perpendicular geometry is the potential for greater optical path lengths, which would produce much larger values of $\theta_{F,\,\mathrm{sat}}$. Other fundamental advantages of this geometry, including reduced hysteresis and greater frequency response, are the result of the domain structure in these films [15].

B. Bulk Iron Garnet Crystals

Significant progress has recently been achieved in the development of novel bulk iron garnet materials [16]. The goal of this ongoing program is to tailor the compositions of bulk iron garnet crystals specifically to optimize their sensing properties, including sensitivity, frequency response, and temperature dependence. Crystals exhibiting a twenty-fold increase in sensitivity (compared to the previously most sensitive iron garnet composition) have been demonstrated under this program. Table I compares the saturation Faraday rotation, normalized magnetooptic sensitivity S', and frequency response of unsubstituted YIG and Ga:YIG with three of these novel garnet compositions. The normalized sensitivity S' is calculated as

$$S' = \frac{SN_D}{L} \tag{2}$$

where S is the measured magnetooptic sensitivity, and L is the sample length. This figure of merit permits the comparison of sensitivities of samples with different geometries. Normalized frequency response data of the samples are shown in Fig. 3. Sample A exhibits a virtually flat frequency response up to 1 GHz, which was the upper limit of the experimental system and exceeds the frequency response even of pure YIG [2]. The general compositions of samples A, B, and C, were $Y_{3-x}B_xFe_5O_{12}$, $Gd_{3-x-y}Bi_xLa_yFe_5O_{12}$, and, $Gd_{3-x}Bi_xFe_{5-y}Ga_yO_{12}$, respectively. The magnetooptical measurements were all performed with a source wavelength of 1.3 μm.

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