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# Novel Bulk Iron Garnets for Magneto-Optic Magnetic Field Sensing

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*Abstract*— **We report measurements of the magneto-optic response function and frequency response for three bulk iron garnet crystals grown by a flux technique. The samples were the product of an intensive effort to develop iron garnet compositions with properties specifically optimized for magnetic field sensing. Sensitivity enhancement was achieved through both bismuth substitution (for increasing the saturation Faraday rotation) and gallium substitution (for reducing the saturation magnetization). One sample exhibited a value of magneto-optic sensitivity of 25°/mT for 1.3 μm light. Frequency response measurements indicate that bismuth substitution actually improves performance (compared to unsubstituted yttrium iron garnet) in contrast with gallium, which causes substantial degradation.**

## I. INTRODUCTION

This paper describes an effort to improve the suitability of iron garnets for Faraday effect magnetic field sensing by enhancing the magneto-optic properties through compositional modification. Historically, these studies have been carried out through the investigation of iron garnet films grown by liquid phase epitaxy (LPE). The main motivation for this work is the optimization of materials grown by the high temperature solution growth method.

In bulk form, both yttrium iron garnet (YIG) and gallium-substituted yttrium iron garnet (Ga:YIG) crystals have been characterized for magneto-optic magnetic field sensing [1,2]. However, even better sensing performance should be possible by using alternative garnet compositions. The primary sensor materials parameters, including magneto-optic sensitivity (the differential Faraday rotation per unit magnetic field), frequency response, and temperature sensitivity, vary widely with composition. For example, bismuth substitution in various iron garnet hosts increases the specific Faraday rotation substantially [3]. The substitution of gallium for iron reduces the saturation magnetization [3,4]. Lanthanum has been added to a terbium iron garnet host to improve its temperature sensitivity [5].

Unfortunately, however, substitutions made for one purpose invariably and unpredictably influence other properties of the crystal. For example, gallium substitution in YIG has the beneficial effect of reducing the saturation magnetization but also reduces both the specific Faraday rotation and the frequency response [2,6]. This example shows the difficulty of choosing an iron garnet composition for a specific application without a model or database to indicate the effect of various substitutions on all of the various sensor material parameters. The strategy employed for this research was to grow a wide array of compositions with a variety of substituents from which a database could be established to identify the appropriate composition for any particular application. From this array, we identified three compositions which effectively represent the variety of characteristics observed in the larger set.

## II. IRON GARNET CRYSTAL GROWTH AND FABRICATION

Bulk single crystals of various garnet compositions were grown by spontaneous nucleation from a $Bi_2O_3/B_2O_3$ flux. The high purity powders were charged into a platinum crucible and heated to a soak temperature of 1300-1330°C. The solution was allowed to cool over several days at 0.7-1.5°C/h through the crystallization region of 1330 to 1050°C. The molten flux was decanted from the crucible at a temperature of around 1050°C, revealing garnet crystals attached to the crucible wall. The crystals were mechanically extracted and cleaned in acid to remove residual flux.

The raw crystals were fabricated into a usable geometry in the form of right cylinders. First, plates of (100) orientation were cut and polished from the crystals. These slices were inspected using a microscope equipped with an infrared video camera. Areas of the crystal which exhibited no visible defects under 100× magnification were selected for further fabrication. These preferred sections of the slices were cubed and machined into cylinders of 2 mm diameter and 0.5-1.2 mm length. Finally, the cylinder endfaces were optically polished to better than 20/10 scratch/dig.

## III. EXPERIMENTAL RESULTS

The three samples selected to represent the array of materials grown for this project are represented by the formulas $Y_{3-x}Bi_xFe_5O_{12}$ (Sample A), $Gd_{3-x-y}Bi_xLa_yFe_5O_{12}$ (Sample B), and $Gd_{3-x}Bi_xFe_{5-y}Ga_yO_{12}$ (Sample C). The sample lengths were 1.18, 1.16, and 1.02 mm, respectively. The sample diameters were all 2.0 mm.

The magneto-optic response function $\theta_F(H)$ of each sample was measured at 1.3 μm using a polarization modulation technique [7]. In each case, the field was swept through one

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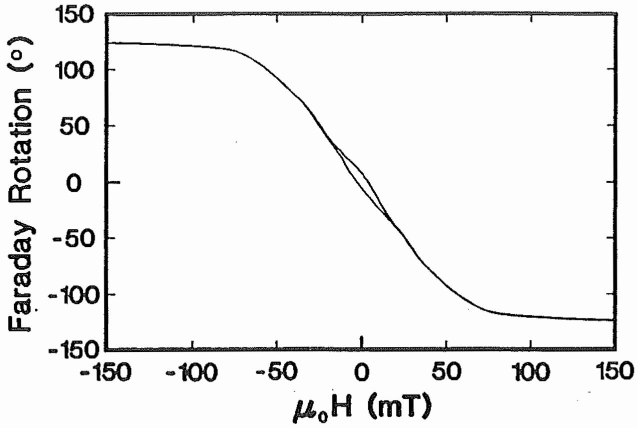

**Fig. 1.** Magneto-optic response function of Sample A.

complete cycle in order to expose any hysteresis. Frequency response measurements between 40 kHz and 1 GHz were conducted with the samples placed inside a dielectric-filled coaxial transmission cell which generated the high frequency magnetic fields. Holes in the cell permitted the transmission of a collimated beam through the sample after which the beam was coupled to a fiber-pigtailed high speed receiver for detection. The magneto-optic response function and frequency response of the Bi:YIG sample (Sample A) are shown in Figs. 1and 2. The response functions of Samples B and C are shown in Figs. 3 and 4. The main features of the data are summarized in Table I. Values for YIG and Ga:YIG ($Y_3Fe_{4.0}Ga_{1.0}O_{12}$) are included in the table for comparison. The tabulated material sensing parameters include the specific rotation (saturation Faraday rotation per unit length), the geometry-independent normalized magneto-optic sensitivity S′, and a qualitative assessment of each material's frequency response. S' is calculated as

$$S' = \frac{S\, N_D}{L} \qquad (1)$$

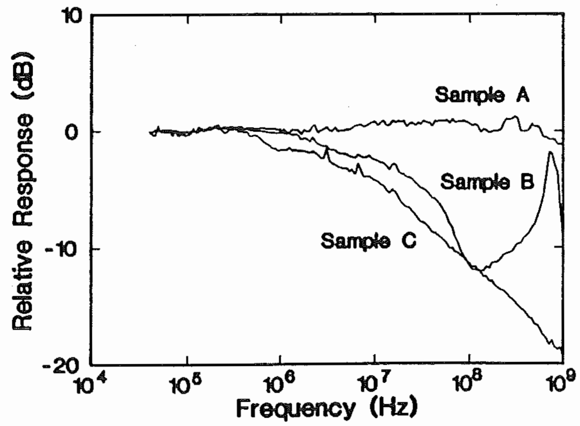

**Fig. 2.** Normalized frequency response data for the three bulk samples described in the text.

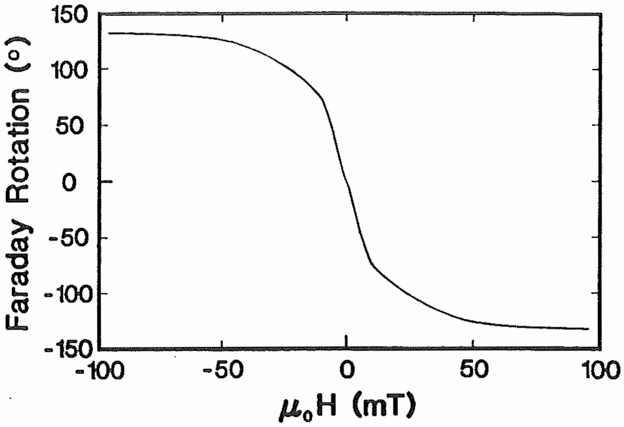

**Fig. 3.** Magneto-optic response function of Sample B.

where S is the measured magneto-optic sensitivity (Faraday rotation per unit magnetic field), $N_D$ is the geometrical demagnetization factor, and L is the sample length.[2]

## IV. Discussion

Samples A and B demonstrate the effect of bismuth substitution into yttrium- and gadolinium-iron garnet hosts, respectively. Both samples exhibit values of specific rotation in excess of 100 °/mm. The higher sensitivity of Sample B is a direct result of a smaller value of saturation magnetization [8]. The frequency response of Sample A, which is virtually flat up to 1 GHz, exceeds that of all the other bulk samples and is matched only by the frequency response of iron garnet films exploited in an optical waveguide geometry [9]. The wide bandwidth of this sample may be related to measurements showing narrower FMR (ferromagnetic resonance) linewidths (indicating less damping) in YIG hosts substituted with bismuth [10]. The resonance exhibited by Sample B near 700 MHz may be associated with domain rotation [11]. One effect which is yet unexplained is the low-field hysteresis observed in the response function of Sample A but not in the response function of Sample B.

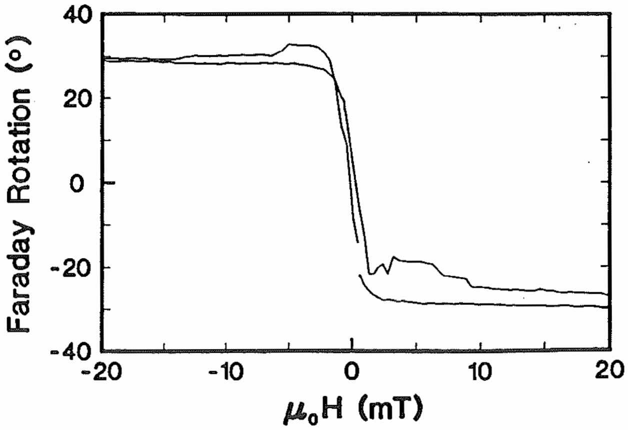

**Fig. 4.** Magneto-optic response function of Sample C.

TABLE I
COMPARISON OF MEASURED SENSING PARAMETERS

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

[a]Values for YIG and Ga:YIG ($Y_3Fe_{4.0}Ga_{1.0}O_{12}$) from Refs. 1 and 2.

Sample C is an example of an attempt to produce the highest magneto-optic sensitivity by simultaneously employing bismuth and gallium substitution. As suggested by the low saturation field evident in Fig. 4, the gallium content in this composition was close to the compensation composition at which $M_{sat}$ vanishes. Nevertheless, the response function exhibits a linear region for fields $|\mu_0 H| < 1$ mT, over which the magneto-optic sensitivity is approximately 25°/mT. A potential drawback to this composition is seen in the frequency response (Fig. 2) which exhibits monotonic rolloff for frequencies greater than a few megahertz.

## V. CONCLUSION

Among the many classes of magneto-optic materials, the ferrimagnetic iron garnets offer by far the greatest magneto-optic sensitivity for magnetic field sensing [1,2]. Iron garnet single crystals in the form of both bulk-grown specimens and epitaxial films have been employed as sensing elements. Each of these morphologies enjoys unique advantages. High quality bulk YIG crystals are commercially available with dimensions from millimeters up to several centimeters and weighing over 200 g. Physically, these dimensions facilitate the integration of these crystals into optical systems using micro-optic lenses (such as those used in fiber optic sensors) but also permit the efficient magnetic coupling of these crystals to flux concentration devices [12]. The chief advantage of epitaxial films has historically been the wider range of available garnet compositions and, as a result, larger values of saturation Faraday rotation $\theta_{F,sat}$. On the other hand, taking full advantage of these large saturation rotation values requires that the films be used in an optical waveguide geometry, which poses other problems including low coupling efficiency and birefringence [9].

The results of this paper demonstrate that iron garnet compositions yielding high values of saturation Faraday rotation can be grown in bulk form suitable for magneto-optic magnetic field sensors. The availability of these materials will permit the construction of magneto-optic magnetic field and electric current sensors which are both faster and substantially more sensitive than sensors based on currently available materials.

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