Magneto-Optic Characterization of Iron Garnet Crystals Using Photoelastic Modulation

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Abstract--Depolarization phenomena in demagnetized bulk iron garnet crystals are investigated with the aid of a photoelastic modulator. An experimental configuration which simultaneously measures Faraday rotation and depolarization as a function of applied magnetic field is described. The technique is demonstrated with samples of SF-57 glass, which exhibits no measurable depolarization, and bulk yttrium iron garnet, which shows pronounced depolarization in the demagnetized state.

I. INTRODUCTION

The photoelastic modulator (PEM) has become a standard tool for polarimetric measurements. However, existing PEM techniques for characterizing magneto-optic materials are strictly valid only when the degree of polarization is unchanged by the material being characterized [1,2]. Although this restriction is satisfied by diamagnetic and paramagnetic materials, it is not always satisfied by unsaturated ferromagnetic and ferrimagnetic materials which exhibit magnetic domain structure and can produce significant spatial depolarization [3,4]. This distinction is particularly important in ferrimagnetic materials such as yttrium iron garnet (YIG), which are used for optical sensing of magnetic fields, and which exhibit the highest sensitivity in the unsaturated (polydomain) state [4,5]. In this paper we present a PEM technique for simultaneously measuring Faraday rotation and depolarization. Other features of this technique are the absence of any moving parts (permitting rapid data acquisition), insensitivity to source (laser) power fluctuations, and the ability to measure Faraday rotation unambiguously between $\pm$ 90°.

II. EXPERIMENTAL

The experimental apparatus consists of a stable 1.32 μm laser source, a polarizer, the PEM, the magneto-optic material (mounted within an electromagnet), a nonpolarizing beamsplitter, two analyzers, and two InGaAs detectors. The analyzers' transmission axes are aligned at 0 and 45° with respect to the polarizer, which is itself oriented at 45° with respect to the PEM axes. With the aid of Mueller matrices [6], we have calculated the time-dependent optical intensities incident on the detectors of this system as functions of the Faraday rotation and depolarization.

III. POLARIZATION MODELLING

The Mueller matrix representing the system described above is given by

$$M_{sys} = M_{an} M_{mo} M_{pem} , \tag{1}$$

where M_{an}, M_{mo}, and M_{pem} are the Mueller matrices for the output analyzer, magneto-optic material, and PEM [6]. M_{mo} is formed from the product of two matrices which separately perform the rotation and depolarization operations. Thus,

$$M_{mo} = M_{dep} M_F , \tag{2}$$

where

$$M_{dep} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & k & 0 & 0 \\ 0 & 0 & k & 0 \\ 0 & 0 & 0 & k \end{bmatrix} \tag{3}$$

and

$$M_F = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta_F & -\sin 2\theta_F & 0 \\ 0 & \sin 2\theta_F & \cos 2\theta_F & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \tag{4}$$

where k is the material's depolarization parameter ($0 \le k \le 1$, with $k = 1$ for nondepolarizing materials) and θ_F is the Faraday rotation. The Mueller matrix for the PEM is

$$M_{pem} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & \sin\delta \\ 0 & 0 & -\sin\delta & \cos\delta \end{bmatrix} , \tag{5}$$

where $\delta = \delta_0 \cos\omega t$, δ_0 is the PEM retardation amplitude, and ω is the PEM modulation frequency. The output Stokes vector of the system is calculated as

$$S_f = M_{sys} S_i , \tag{6}$$

where S_i is the initial Stokes vector for the input

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polarization state which is linearly polarized at 45°. Calculation of Eq. (6) for the two cases of M_{an} leads to equations for the intensities at the two detectors. These equations are

$$I_1 = K_1 \frac{1 - k \sin 2\theta_F \cos\delta}{2} \tag{7}$$

and

$$I_2 = K_2 \frac{1 + k \cos 2\theta_F \cos\delta}{2} , \tag{8}$$

where I_1 and I_2 refer to the intensities incident on the detector with its analyzer oriented at 0 and 45°, respectively, and K_1 and K_2 are constants depending only on the source power and beamsplitting ratio. The time-varying term, $\cos(\delta_0 \cos\omega t)$, can be expanded in a Bessel function series which yields a dc component in addition to components which vary as $\cos(2\omega t)$, $\cos(4\omega t)$, etc. [1,2]. We find that the intensity at each detector can be well approximated as the sum of the dc and the 2ω components. Specifically, the amplitudes of these components are

$$I_{1,DC} = K_1[1 - k \sin(2\theta_F) J_0(\delta_0)]/2 , \tag{9}$$

$$I_{2,DC} = K_2[1 + k \cos(2\theta_F) J_0(\delta_0)]/2 , \tag{10}$$

$$I_{1,2\omega} = -K_1 k \sin(2\theta_F) J_2(\delta_0) , \tag{11}$$

and

$$I_{2,2\omega} = K_2 k \cos(2\theta_F) J_2(\delta_0) , \tag{12}$$

where J_0 and J_2 are the standard Bessel functions.

IV. Signal Processing

$I_{1,DC}$ and $I_{2,DC}$ are measured with dc voltmeters, and $I_{1,2\omega}$ and $I_{2,2\omega}$ with lock-in amplifiers. δ_0 is fixed at 2.41 rad (138°), which corresponds to the first zero of J_0 and makes $I_{1,DC}$ and $I_{2,DC}$ equal to $K_1/2$ and $K_2/2$, respectively. These signals are then used to normalize $I_{1,2\omega}$ and $I_{2,2\omega}$, and permit the direct calculation of $k\sin(2\theta_F)$ and $k\cos(2\theta_F)$. Thus, by measuring the amplitude of the dc and 2ω components in each detector's output, we can determine k and θ_F independently without sensitivity to the source power, beamsplitting ratio, or differing detector responsivities. Moreover, θ_F may be determined unambiguously between values of ± 90°, which is twice the unambiguous range provided by simple differential detection.

V. Results and Discussion

The technique has been successfully tested on one sample of SF-57 glass (10 cm length) and two specimens of bulk yttrium iron garnet, YIG (5 mm diameter by 3 mm and 5.6 mm length). For all three samples, data were recorded as the applied magnetic field was swept through one entire cycle. Glass was chosen to test the technique because of its linear magneto-optic properties as well as its lack of depolarizing effects. In addition, SF-57 is generally free of stress-induced birefringence, which would invalidate the proposed Mueller-matrix model.

In the demagnetized state, bulk YIG crystals are expected to exhibit depolarization effects because of inhomogeneous magnetic domain structure. Parallel paths through a YIG crystal will generally pass through different domains of varying size and magnetization direction. For a given path, the total Faraday rotation is proportional to the line integral of the magnetization component parallel to the propagation direction. Thus, the total Faraday rotation will generally vary for parallel paths through the YIG crystal. If the crystal is probed with a collimated beam which is significantly larger than the typical domain, the beam leaving the crystal will exhibit spatial depolarization.

As shown in Figs. 1 and 2, SF-57 exhibits the expected linear dependence of Faraday rotation on applied field with no apparent field-dependent depolarization. (We attribute values of $k > 1$ to a normalization error caused by a frequency dependence of either the detectors or detector amplifiers which is not cancelled by the ac/dc ratio technique.) These data confirm the predicted behavior of the PEM technique. In contrast, the YIG samples exhibit regions of nonlinear Faraday rotation and significant depolarization. The depolarization in the longer bulk YIG crystal is significantly greater than in the shorter sample. For both samples, the degree of polarization increases as the material nears saturation where the YIG sample approaches a single domain state, which is magnetically homogeneous.

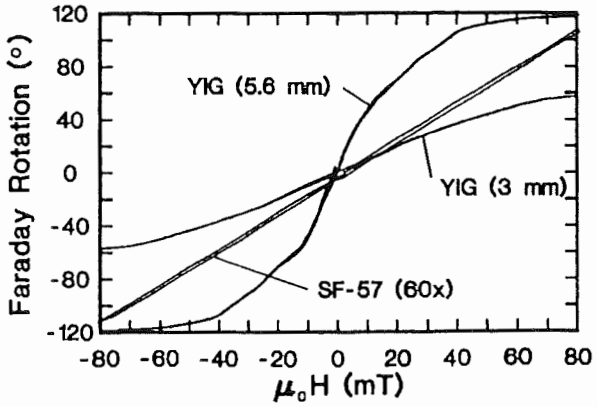

Figure 1. Faraday rotation versus applied magnetic field. The vertical scale for SF-57 is expanded 60×.

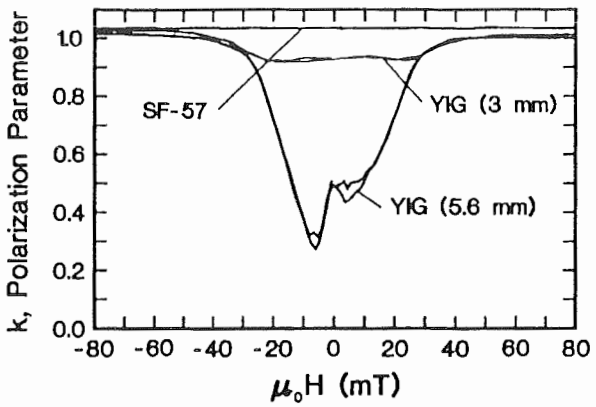

Figure 2. Polarization parameter (k) versus applied magnetic field. Values of k > 1 are attributed to a normalization error associated with the detectors.

VI. Conclusion

A polarization-modulation technique for simultaneously monitoring Faraday rotation and depolarization has been demonstrated. The technique was successfully tested with SF-57 glass which exhibited linear Faraday rotation and a constant degree of polarization. Unrealistically large values of the degree of polarization are thought to be due to a normalization error associated with the optical detectors. Demagnetized bulk YIG crystals exhibit depolarization which appears to increase with the length of the crystal and decrease with applied magnetic field.

References

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