Fiber Based Measurements of Domain Characteristics in Bismuth Substituted Iron Garnets

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***Abstract*—Bismuth substituted iron garnets (BIGs) are magneto-optic materials which exhibit Faraday rotation in an applied magnetic field. In the absence of an applied field, individual domains still exhibit Faraday rotation, though the bulk material does not. Using single mode fiber where the half power beam width is smaller in dimension than the magnetic domains of the material, individual magnetic domains of BIG samples are identified. A method for differentiating domains and determining domain alignment is presented. The Faraday rotation of individual domains is measured and reported.**

***Index Terms*—Bismuth substituted iron garnets, Faraday rotation, fiber-based magneto optics, magnetic domains, optical beam size**

I. INTRODUCTION

As demand grows for higher bandwidth networks, optical communication technologies have been increasingly utilized and researched. In [1] and [2] our team proposed an all optical Mach-Zendher interferometer (MZI) type switch that utilizes the magneto-optic properties of bismuth substituted iron garnet (BIG). This material exhibits Faraday rotation, the rotation of the state of polarization (SOP) of linearly polarized light in an applied magnetic field, and a sample is placed in each path of the MZI. In the switch, an incoming beam of linearly polarized light is split into the two paths of the interferometer using a 3dB coupler. In the absence of a magnetic field, the light passes through each path maintaining its original SOP and is recombined at the output with a second 3dB coupler resulting in an "ON" state. In an applied field, the SOP of the light undergoes a rotation proportional to the magnitude of the applied field. By applying an appropriate field, the SOP can be rotated in each path such that destructive interference at the output of the second 3dB coupler results in an "OFF" state. ON/OFF extinction ratios of 8.5 dB for single mode fiber (SMF) and 12.5 dB for multimode fiber (MMF) have been experimentally realized and reported [2] with an applied field of 200 Oe.

In designing a more efficient switch, special attention has been focused on the careful fiber based study of the magneto-optic properties of the BIG samples. Specifically, by confining an incident beam of the fiber predominantly to a single domain, the domain behavior of the material can be studied. In this paper we discuss new finding and results of measurements of Faraday rotation which can lead to a better physical understanding of the magneto optic Faraday rotator (MOFR).

II. MAGNETO OPTIC PROPERTIES OF BIGS

Before the discovery of BIGs, yttrium iron garnets (YIGs) were used in magneto optic devices because of their low optical absorption and reasonable Faraday rotation. Upon their discovery, BIGs were found to have a number of advantages over YIGs, including negligible birefringence, higher Faraday rotation (θ) to optical absorption (α) ratio, a significant figure of merit for a MOFR, and adaptability to the use of advanced epitaxial growth techniques [3],[4]. Faraday rotation in BIGs increases for shorter wavelengths. One disadvantage BIGs exhibit over YIGs is a higher temperature coefficient of Faraday rotation, for which compensation methods have been proposed [5].

As suggested in [3], due to the Faraday effect and the domain size, magnetic domains can be investigated in bismuth substituted garnets thin films. The particular samples used in this study are bismuth substituted iron garnet $[(Bi_{1.1}Tb_{1.9})(Fe_{4.25}Ga_{0.75})O_{12}]$ with a saturation field of approximately 350 Oe. Using magnetic force microscopy, the magnetic domains in the sample have been determined to be about 20 μm wide. The samples have a thickness of 330 μm and the refractive index is about 2.344 at 1550 nm. Thus, the MOFR is about 500 wavelengths long, and therefore, the fiber modes are expected to be maintained in the rotator.

Bismuth substituted terbium iron garnets are a ferrimagnetic material, which results in magnetic domains with alternately aligned magnetic moments [6]. If a beam of linearly polarized light passing through the material samples a large number of

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domains, it undergoes a rotation $\theta_{effective}$ described by the relation $\theta_{effective}=\theta_{sat}(H_{app}/H_{sat})$ where θ_{sat} is the rotation experienced in a saturation field H_{sat} and H_{app} is the applied field to the MOFR. When the beam is not sufficiently large and a single domain or a small number of domains are sampled, the previous relation does not apply and the local characteristics of the individual domains play an important role in the Faraday rotation. It should be noted that each domain has an internal magnetic moment, so even in the absence of an external applied field, a beam passing through a single domain will be acted on and undergo Faraday rotation.

III. FIBER BASED OPTICAL MEASUREMENTS

Much of the investigation of magneto-optic materials has been done using free space optics. Utilizing fiber however, offers many advantages and allows for new possibilities for experimental studies. One of the most interesting possibilities when utilizing optical fibers is the much narrower beam size. The measurements are limited by the diameter of the beam incident on the material.

The beam from a MMF, which has a core diameter of about 62.5 µm, will sample a number of domains. The beam from a SMF, with a core diameter of approximately 9 µm, can be confined to a very small number or even a single domain. This allows for the examination of how an individual domain acts on polarized light.

The experimental setup is shown in Figure 1. Using a laser, a linearly polarized beam can be produced and a mode stripper can be used to help ensure only a single mode is present in a SMF. The MOFR can be placed between two aligned fibers, one transmitting and the other receiving. Using a polarization analyzer and an optical power sensor, the SOP of the incident beam and the beam which has passed through the MOFR can be determined, allowing for the determination of Faraday rotation. The BIG sample can be precisely positioned between the fibers so that that the rotation can be measured in multiple domains and at domain walls. This method was utilized to measure Faraday rotation in the domains and the results are reported in the 'Experimental Setup and Results' section of this paper.

IV. DOMAIN DIFFERENTIATION

Utilizing a linearly polarized source and a linear polarizing filter of adjustable orientation, individual domains can be differentiated and their alignment determined. When linearly polarized light passes through a polarization filter, the transmitted power is described by $P_{out}=P_{in}\cos^2\alpha$ where α is the angle between the polarizing filter and the polarization axis of the incident beam. It is expected that domains with magnetic moments parallel to the direction of transmission will rotate the SOP by an amount φ while domains with magnetic moments anti-parallel to the direction of transmission will rotate the SOP by an amount -φ. By aligning a linear filter perpendicular to the polarization axis of the incident beam, significant contrast can be seen between regions of the sample where Faraday rotation occurs (aligned and anti-aligned domains) and regions where no Faraday rotation occurs (domain walls). In this way, regions of the sample where the beam experiences Faraday rotation can be differentiated from regions where it does not.

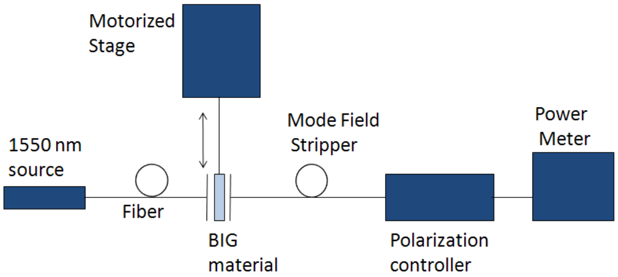

Figure 1: Experimental setup with SMF used to locate domains in BIG

Further knowledge of the domain structure can be obtained by aligning the linear polarizer to have minimum power transmission when the beam is transmitted through a domain where it undergoes a rotation φ. This will allow the investigator to differentiate between domains that are aligned with the direction of propagation and domains that are anti-aligned. When the beam penetrates a region of the material where the domains are anti-aligned (assuming a rotation of -φ) the resulting SOP will have an angle of 2φ relative to the minimum transmission and therefore the output power in an anti-aligned domain is described by: $P_{out}=P_{in}\cos^2(90-2\varphi)$.

As described in the next section, both of these methods were realized experimentally. By using a combination of the two methods described above, an experimenter can discern both the location and alignment of magnetic domains.

V. EXPERIMENTAL SETUP AND RESULTS

Using the lateral offset method, the half power beam width (HPBW) incident on a BIG sample 1 mm from the transmitting beam was determined to be approximately 16 µm. In order to differentiate the domains as described in the previous sections, the following experimental setup was utilized. An Agilent 81640a 1550 nm laser was used to produce linearly polarized light and was guided though a SMF with a mode stripper. The end of a second SMF was aligned with the output end of the first. The second fiber, which also had a mode stripper, was connected to an Agilent 8169a polarization controller and then to an Agilent 81635 optical power sensor. A BIG sample was placed between the two fibers. The sample was on a motorized microstage with a 7.5 nm step size.

Using the procedure outlined in the previous section, domains were differentiated and located within the material. In the first setup, the polarizer was set perpendicular to the polarization axis of the incident beam. The power received when the beam is transmitted though an aligned or anti-aligned domain is approximately 25 dB higher than when the beam is transmitted through a domain wall. In order to determine domain alignment, the polarizer is set perpendicular to the polarization axis of the beam after it has traveled through an aligned domain. The average power contrast between the transmission through anti-aligned domains and aligned domains is 15 dB.

The Faraday rotation in the domains was then measured. This was done by first adjusting the angle of the polarization analyzer θ_1 so that minimum power was received when the sample was not in between the two fibers – the polarizer was set perpendicular to the polarization of the incident beam. Using the motorized stage, the sample was then positioned so that the beam passed though a domain. The polarization analyzer was adjusted to find the angle θ_2 where the minimum power was received – the polarizer was set perpendicular to the polarization of the beam that passed through a domain where it had undergone Faraday rotation. The difference θ_1-θ_2 is the Faraday rotation of the SOP of the beam.

The average magnitude of Faraday rotation measured in the domains was 32° with a standard deviation of 17°. In most cases, domains neighboring each other were found to have rotation in opposite direction.

VI. CONCLUSION

In this paper, a method for using fiber based measurements to examine the magneto optic effects of BIG samples was presented. Domains were successfully differentiated and domain walls were also located within the samples. A method for determining the alignment of the magnetic domains was presented and experimental results were provided. Faraday rotation was measured in aligned and anti-aligned domains. Because the beam size of a SMF can be confined to an area on the scale of the domain size, fiber based measurements offer many advantages in studying magneto optic effects such as Faraday rotation in magnetic materials.

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