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Research articles

Magnetization spin dynamics in a $(LuBi)_3Fe_5O_{12}$ (BLIG) epitaxial film

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ABSTRACT

Bismuth substituted lutetium iron garnet (BLIG) films exhibit larger Faraday rotation, and have a higher Curie temperature than yttrium iron garnet. We have observed magnetic stripe domains and measured domain widths of 1.4 μm using Fourier domain polarization microscopy, Faraday rotation experiments yield a coercive field of 5 Oe. These characterizations form the basis of micromagnetic simulations that allow us to estimate and compare spin wave excitations in BLIG films. We observed that these films support thermal magnons with a precessional frequency of 7 GHz with a line width of 400 MHz. Further, we studied the dependence of precessional frequency on the externally applied magnetic field. Brillouin light scattering experiments and precession frequencies predicted by simulations show similar trend with increasing field.

1. Introduction

Spin waves also known as magnons, have been extensively explored in the past decade for a variety of magnetic devices like multiplexers, logic gates, waveguides and resonators [1–5]. There have been recent experimental demonstrations of magnetic domain walls as re-configurable nano sized magnonic waveguides [6]. The preferred choices of ferromagnetic materials for these devices are permalloy and CoFeB. Another class of popular materials include insulating ferrimagnetic materials, or ferrites, like yttrium iron garnet (YIG) and bismuth substituted lutetium iron garnet (BLIG). We know that the spin wave decay length in permalloy is 3 orders shorter than that of ferrites. BLIG ($(LuBi)_3Fe_5O_{12}$) also exhibits a higher Faraday rotation, at a higher Curie temperature, than YIG. This makes BLIG films better candidates for use in magneto-optic devices [7].

Ferrite films can be used for novel applications such as magneto-optic Q switching [8]. They have been used in a wide variety of other applications [9] and are also being considered for demonstrating logic devices such as majority gates with fast clocking frequencies [10].

In this work, we characterize an optically transparent BLIG film of thickness 7.9 μm, epitaxially grown over a gadolinium gallium garnet (GGG) substrate [7,11]. We first measure the magneto-static and magneto-optic properties of these films, using external magnetic fields. We then use the parameters extracted from the static analysis in the micromagnetic simulations to study the dynamic properties of the thermally excited spin waves. Finally, we use Brillouin light scattering (BLS) experiments to corroborate the predictions of micromagnetic simulations. For measurement of Faraday rotation and coercivity, we designed and used the Magneto optic Faraday effect (MOFE) experiment discussed in Section 2. In Section 3, we characterize striped domain patterns observed using a transmission mode polarization microscope (PM). Degaussing the film, by applying alternate positive and negative decreasing magnetic fields, produces orderly striped domain patterns. When observed in the Fourier plane of the microscope, these orderly domains show a diffraction pattern similar to a 1D grating.

In Section 4, we extract the properties of BLIG from the previous static measurements and simulate the multiple stripe domains using the micromagnetic solver MuMax3 [12]. We allow the simulations to relax to a ground state where the film has a domain width, which is decided by the initial magnetization. To the best of our knowledge, dynamic micromagnetic simulations of magnetic oscillations in stripe domain structures have not been reported elsewhere.

We begin with a theoretical estimate of parameters like magnon frequency and domain wall frequency. We then include thermal fluctuations and external magnetic fields to the static multi domain simulation model for the dynamic analysis. Brillouin light scattering (BLS) measurements, at room temperature, confirm our

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estimated increase in magnon frequency with an increase in external magnetic field, as discussed in Section 5.

2. Hysteresis measurements

The MOFE set-up shown in Fig. 1, consists of a He–Ne laser ($\lambda = 633$ nm) with an average power of 2.5 mW, a polarizer and an analyzer, and a power meter with a measurement range of 50 nW–50 mW. We use a pair of electromagnets with a maximum magnetic field of ± 600 Oe to provide the external magnetic field. The procedure to obtain the Faraday rotation (θ_F) from the film as a function of the applied magnetic field ($\mathbf{H}_{app}$) is as follows:

- We first obtain the change in transmitted optical power (P_{tr}) as a function of analyzer angle (θ_{an}). This will follow Malus' law

$$P_{tr} = P_0 \cos^2(\theta_{an} + \phi), \quad (1)$$

  The values of P_0 and ϕ account for any misalignment and absorption that occur in the setup. The variation in transmitted power is shown in Fig. 2.
- We then measure the variation of P_{tr} with an applied magnetic field and map this to a variation in Faraday rotation angle using (1). This variation is shown as the hysteresis loop in Fig. 3.

The film shows low coercivity of ~ 5 Oe, which indicates that the magnetization lies in the plane of the film. The film also shows a low remanence of 15% of M_s which is consistent with soft magnetic materials.

3. Domain imaging using polarization microscopy (PM)

We use polarization microscopy to observe the spatial orientation of the magnetic domains in these ferrite films. The setup consists of a transmission mode optical microscope with two linear polarizers in a cross axis polarizer–analyzer configuration. The light from a tungsten halogen lamp, after passing through the polarizer is incident on the sample and collected using a 20× objective. The analyzer, which is in a cross axis configuration placed after the objective in the optical path, diminishes the direct transmission and obtains the dark field images which is captured by a CCD camera. In Fig. 4 the images obtained show stripes of alternating intensity patterns attributed to domains of opposite in-plane magnetization, resulting from a differential Faraday effect.

We observed uniformly magnetized domains along the in-plane easy axes. With the film thickness in microns, domains should be separated by straight parallel Bloch walls. In the absence of any externally applied field, and when the film is demagnetized, we observed that the total volumes of the two sets of domains were equal, and the walls were equally spaced. The spacing of the walls is governed by a host of competing factors. The exchange and anisotropy energies of the walls favour wide domains while the dipolar energy of the domains favours closely spaced walls. The spacing of the walls is a compromise between these effects to achieve minimum energy state [13]. This was evident on the application of a magnetic field to the demagnetized films in a direction parallel to the domains. With an increase in magnetic field, each domain experiences a torque that tends to turn it in the direction of the applied field. As a result, the exchange energy increases and domains grow wider, finally becoming single domain at ≈100 Oe.

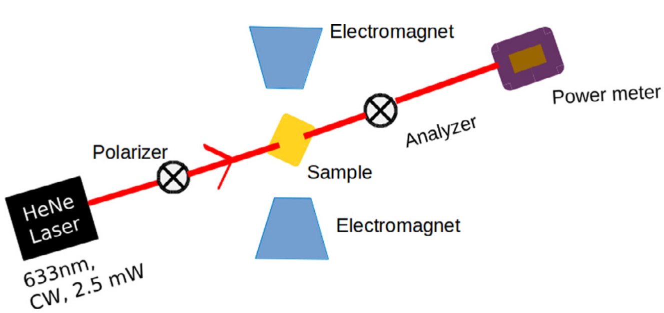

Fig. 1. MOFE experimental setup to measure Faraday rotation.

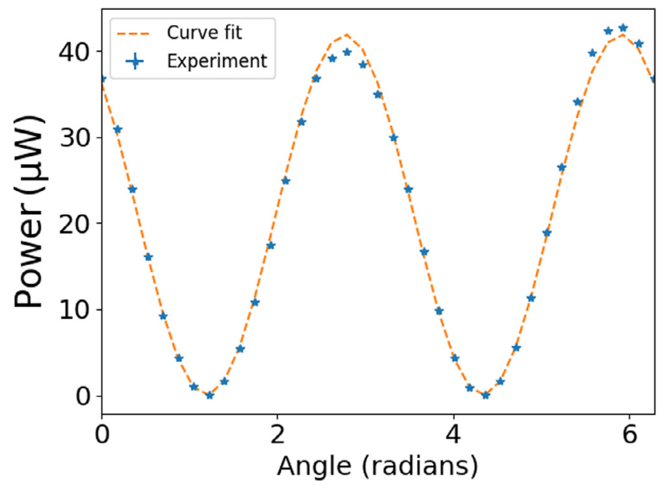

Fig. 2. Transmitted optical power as a function of rotation of analyzer angle. The dashed line shows a fit to (1).

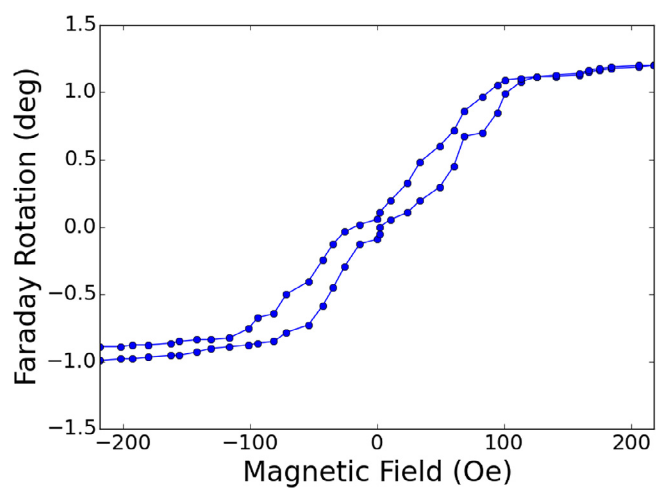

Fig. 3. Hysteresis loop of the film obtained by Faraday rotation.

We can infer the average domain width from PM images using a Fourier spectrum of the scan along the black dotted line in Fig. 4(a). The Fourier spectrum of the scan in Fig. 4(b), shows a single peak giving us a period of domain $\lambda_{DW} = 2.8$ µm. Since one period in Fig. 4(a) consists of oppositely aligned domains, this gives us a domain width of $\delta = 1.4$ µm.

The Fourier domain image of the sample, as shown in Fig. 5(a) is viewed by placing a concave lens in the optical path of the microscope after the analyzer. The multiple spots correspond to diffraction orders from the magneto-optical grating formed by the alternating domains which are similar to the diffraction patterns obtained from bi-periodic stripe domains [14]. We observed a rotation of the diffraction orders on changing the direction of magnetic field which has been discussed elsewhere [15]. We also observe 'fork' domain patterns shown in Fig. 5(b) in our films, which mark regions where the alignment of the domains changes significantly.