Brillouin light scattering detection of ferromagnetic resonance in thin films

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Ferromagnetic resonance (FMR) in thin films of permalloy and yttrium iron garnet (YIG) has been studied by Brillouin light scattering (BLS) techniques. The measurements were made at 9.4 GHz on 22.4 to 75-nm-thick permalloy films and on 2.1- to 12.8-μm-thick YIG films. Intensity profiles for magnon scattered light versus in-plane applied field were obtained by analyzing the forward scattered light through the films with a high-contrast Fabry–Perot interferometer. The BLS profiles show a signal-to-noise ratio of 10-100 for the permalloy and 100-1000 for the YIG films, depending on the film thickness and the microwave power level. The FMR BLS response was quantified in terms of global response function, counts/s mW versus magnon occupation number N_u. The N_u parameter relates the scattering to the uniform mode FMR response (linewidth, field, frequency, etc.), input microwave power, and active sample volume. The response for permalloy was approximately 10^{-8} counts/s mW magnon, which translates into a limiting sample volume of 10^{-12} cm^3.

I. INTRODUCTION

With the development of high-contrast Fabry–Perot interferometry, the Brillouin ligh scattering (BLS) technique has been used to study ferromagnetic resonance (FMR) in a variety of materials. These BLS applications include FMR in yttrium iron garnet (YIG),[1,2] Fe films,[2] $FeBO_3$,[2,3] and K_2CuF_4,[4] and antiferromagnetic resonance in $CoCO_3$.[5,6] These studies focused primarily on relaxation and spin-wave phenomena. The purpose of this work is to make quantitative sensitivity determinations for the BLS detection of FMR. These present measurements were for permalloy and YIG films.

In the BLS technique for FMR, static and high-frequency fields are applied as with conventional microwave techniques. Rather than measuring the absorbed microwave power, however, one uses a high-contrast Fabry–Perot interferometer (FPI) to detect the light which is scattered by the driven FMR magnon modes in the material. A plot of the scattered light intensity versus static magnetic field yields an FMR peak or peaks similar to the usual microwave absorption versus field profiles for conventional FMR. The main advantage of the BLS technique for FMR studies is in the achievement of a reasonably high signal-to-noise ratio for small working sample volumes. With a high-contrast multipass tandem FPI, it is possible to achieve a sensitivity that is comparable to that for conventional microwave spectrometers, but for sample volumes on the order of 10^{-12} cm^3.

II. EXPERIMENTAL TECHNIQUE

The experimental setup used for the BLS observation of FMR is shown in Fig. 1. The linearly polarized incident light is focused onto a sample which is properly positioned in a microwave cavity or shorted waveguide section, and located in a static magnetic field. A backscattering geometry indicated by the dashed lines is used for accurate collection lens positioning.

A forward-scattering arrangement indicated by the dotted line is used for FMR. The forward-scattering arrangement is useful in order to probe the low, near-zero wavenumber mode or modes which are usually associated with ferromagnetic resonance. This means that the technique is limited to reasonably transparent films which are thin enough to pass some fraction of the incident light. The forward-scattered light through the sample passes through a polarization analyzer, a diaphragm, and aperture arrangement, and then to a high-contrast 4 + 2 pass tandem FPI system. The photon-counting system consists of a low dark count photomultiplier tube (PMT). The Brillouin spectrum is recorded with a multichannel analyzer (MCA).

The setup for microwave excitation of the samples consists of a 200-mW frequency stabilized klystron, an attenuator to control the input power, and a TE_{102} reflection-type cavity or a shorted waveguide section. The cavity was used for the permalloy and the shorted section was used for the

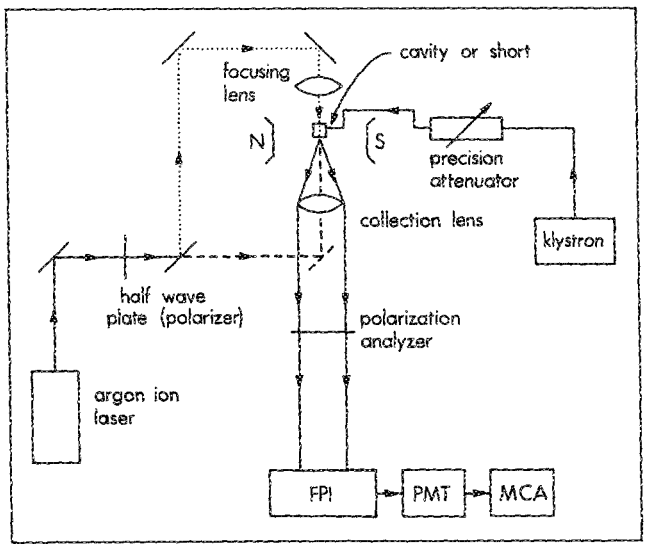

FIG. 1. Schematic diagram of the experimental setup used for the Brillouin light scattering detection of ferromagnetic resonance (FMR) in thin films.

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YIG. A static magnetic field was applied parallel to the film plane and perpendicular to the in-plane microwave field.

The basic light scattering FMR signal is a peak in the BLS spectrum of intensity versus frequency. A representative BLS spectrum for FMR in permalloy films is shown in Fig. 2. The spectrum is for a 22.4-nm-thick film, a drive frequency of 9.4 GHz, an in-plane static field of 914 Oe, and a microwave field of 700 mOe at the sample. The peaks at $\pm$ 9.4 GHz are due to the FMR magnons excited in the permalloy. The central Rayleigh peak at zero-frequency shift corresponds to unshifted laser light, and the peaks at $\pm$ 50 GHz are due to neighboring interference orders.

Profiles of the magnon scattered light intensity for the peaks at $\pm$ 9.4 GHz versus static field were obtained using the continuous scan technique described in Ref. 7. In this technique, scattering events over the frequency range of interest, that is, the magnon scattering at $\pm$ 9.4 GHz in Fig. 2, are counted and accumulated in successive MCA storage channels as the external applied field is slowly varied. The signal-to-noise ratio for such profiles can be enhanced by a factor of 10 by increasing the scan time of the FPI over the frequency range of interest.[7] BLS-FMR profiles obtained by this procedure for the permalloy and YIG films are presented in the next section.

III. RESULTS FOR PERMALLOY AND YIG

The BLS-FMR measurements were done on a series of permalloy films with thicknesses of 22.4, 40, and 75 nm, and on 2.1, 4.2, and 12.8-μm-thick epitaxial YIG films on gadolinium gallium garnet substrates. The permalloy and YIG films consisted of 4- and 2-mm squares, respectively. Companion microwave absorption profiles were obtained by simultaneously monitoring the microwave power reflected from the cavity (permalloy) or the waveguide short (YIG).

A typical BLS profile of scattered intensity versus field for permalloy film FMR is shown in Fig. 3(a). Figure 3(b) shows the companion microwave absorption profile. These profiles are for the 22.4-nm-thick film and a microwave field amplitude of 500 mOe. The observed BLS intensity versus field profile closely tracks the microwave response. The resonance linewidths, or width of the profiles at half power, are about 40 Oe in both cases, typical for thin permalloy films at X-band frequencies. It is apparent that the microwave profile is somewhat "cleaner," with a higher signal-to-noise ratio (SNR), than the BLS profile. It is important to note that the BLS profile corresponds to a very small effective volume. For a focusing spot size of 50 μm, the working volume for the BLS signal is about 4×10^{-11} cm^3, compared to the total sample volume of 4×10^{-7} cm^3 for the microwave experiment. Even for such a small working volume, the BLS profile shows a SNR of about 50. The permalloy films SNR ranged from 10 to 100, depending on the film thickness and the microwave power.

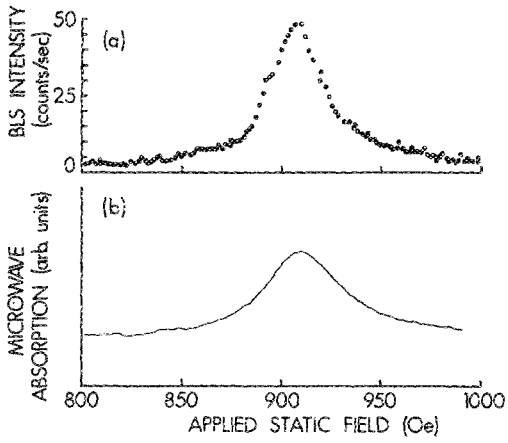

FIG. 3. Profiles of (a) intensity of magnon scattered light and (b) microwave absorption vs in-plane static magnetic field for FMR at 9.4 GHz in a 22.4-nm-thick permalloy film. The microwave field amplitude at the sample was 500 mOe and the incident laser power was 4 mW.

Similar intensity versus field profiles were obtained for the YIG films. One such profile for the 4.2-μm-thick film is shown in Fig. 4, along with the companion microwave profile. As noted above, the YIG data were obtained with a shorted waveguide excitation structure. The narrow linewidth and strong FMR absorption precluded the use of a cavity for the YIG measurements. The BLS profiles shows several magnetostatic modes which are not resolved in the microwave experiment. The BLS profiles for the YIG films had SNR values of 100–1000. The SNR is higher for the YIG than the permalloy because of the higher working volume

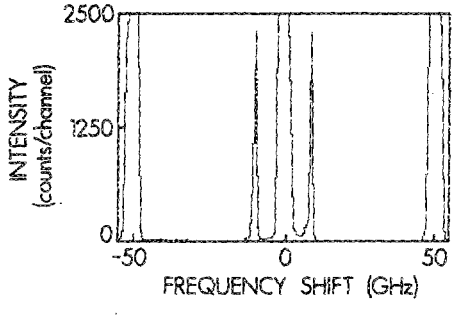

FIG. 2. Brillouin spectrum for 9.4-GHz FMR in a 22.4-nm-thick permalloy film. The microwave field was 700 mOe and the in-plane static field was 914 Oe. The incident laser power was 16 mW.

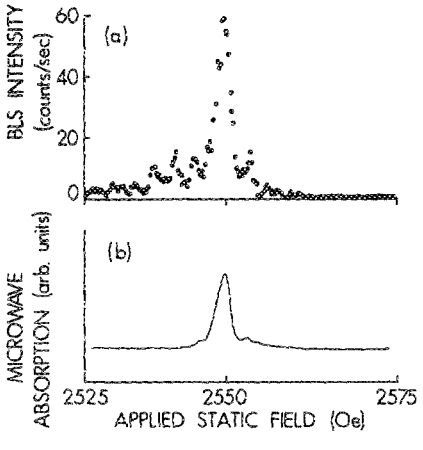

FIG. 4. Profiles as in Fig. 3, but for a 4.2-μm-thick yttrium iron garnet film on a gadolinium gallium garnet substrate for a microwave field amplitude of 28 mOe at the sample and an incident laser power of 8 mW.

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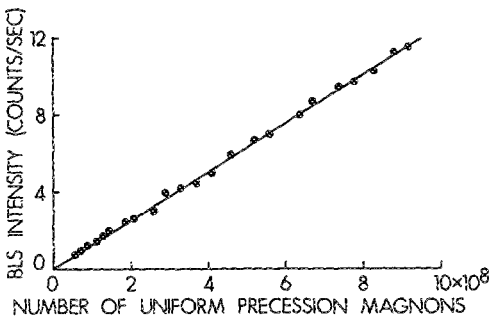

FIG. 5. Data on intensity of magnon scattered light vs number of uniform precession magnons excited in the volume of the sample probed by the incident light for a 22.4-nm-thick permalloy film. The incident laser power was 4 mW.

and larger magneto-optic coefficients, in spite of the lower saturation induction.

IV. BLS RESPONSE AND MAGNON OCCUPATION NUMBER

The results presented above demonstrate the use of BLS techniques for the observation of FMR in thin films. This section presents brief comments on magnon occupation numbers and sensitivity limits for the BLS detection of FMR.

One can estimate the BLS sensitivity limits for FMR detection in terms of the magnon occupation number required for detectable scattering. Such an exercise was carried out for the thinnest permalloy film, 22.4 nm, by measuring the intensity of magnon scattered light as a function of number of uniform precession magnons N_u excited at resonance in the volume of the sample probed by the incident beam. For an in-plane magnetized film, N_u at ferromagnetic resonance is given by

$$N_u = (M/8\gamma\hbar)(1+\gamma H_r/f)\left[1+\gamma(H_r+4\pi M)/f\right] \times (h_m/\Delta H)^2 V. \quad (1)$$

In Eq. (1), $4\pi M$ is the saturation induction, γ is the gyromagnetic ratio, $\hbar$ is the Planck's constant, H_r is the resonance field, f is the FMR frequency, ΔH is the linewidth, h_m is the linearly polarized microwave field amplitude, and V is the sample volume. For the permalloy film, the numerical values of the above material parameters are $4\pi M = 10.5$ kG, $\gamma = 2.96$ GHz/kOe, and $\Delta H = 43$ Oe. Figure 5 shows the BLS intensity vs N_u data for an incident laser power of 4 mW. The variation in N_u was achieved by changing the input microwave power. The linear response in Fig. 5 shows that the scattering scales linearly with input microwave power, as one would expect in the small signal regime. The measured response translates into a scattering cross section of approximately 3×10^{-9} counts/s mW magnon. This number, in conjunction with Eq. (1), provides a useful response parameter for the BLS detection of FMR. One can use this value to estimate the expected scattering as a function of laser power, FMR field and/or frequency, magnetization, linewidth, and microwave field amplitude (cavity power).

In line with the above results, one can estimate limiting sample volumes for the BLS detection of FMR peaks. The operational photon detection limit due to photomultiplier tube dark count is about 1 count per second. For the data in Fig. 5, this translates into a minimum sample volume of about 4×10^{-12} cm^3 at $h_m = 1$ Oe. For a 10-nm-thick film, this corresponds to a film diameter of about 5–10 μm. Given the fact that BLS techniques can detect thermal magnon populations, such small limiting volumes are not particularly surprising. Nevertheless, quantitative scattering cross-section data, as in Fig. 5, should prove useful in setting up BLS-FMR experiments for bulk materials, thin films, superlattice structures, and monolayer systems.

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