Characterization of spin wave propagation in (1 1 1) YIG thin films with large anisotropy

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Received 6 February 2017, revised 27 March 2017
Accepted for publication 19 April 2017
Published 22 May 2017

Abstract
We report on long-range spin wave (SW) propagation in nanometer-thick yttrium iron garnet (YIG) film with an ultralow Gilbert damping. The knowledge of a wavenumber value $k$ is essential for designing SW devices. Although determining the wavenumber $k$ in experiments like Brillouin light scattering spectroscopy is straightforward, quantifying the wavenumber in all-electrical experiments has not been widely commented upon so far. We analyze magnetostatic spin wave (SW) propagation in YIG films in order to determine the SW wavenumber $k$ excited by the coplanar waveguide. We show that it is crucial to consider the influence of magnetic anisotropy fields present in YIG thin films for precise determination of SW wavenumber. With the proposed methods we find that experimentally derived values of $k$ are in perfect agreement with that obtained from electromagnetic simulation only if anisotropy fields are included.

Keywords: spin waves, ferromagnetic resonance, low damping materials

(Some figures may appear in colour only in the online journal)

1. Introduction
Spin wave (SW) propagation in magnetic thin film structures has become an intensively investigated topic in recent years, due to promising applications in modern electronics [1–4]. The wavenumber (or equivalently—the wavelength $\lambda = 2\pi/k$) is an important parameter to account for propagation characteristics. For example, it is essential to choose a SW wavenumber and correlate it to a certain device dimension in order to ensure observation of the expected phenomena in SW devices e.g. in magnonic crystals [5, 6] or devices based on wave interference, such as SW transistors [2], SW logic gates [2] and Mach–Zehnder type interferometers [7]. The knowledge of the SW wavenumber is also very important in the assessment of the effective magnitude of the Dzyaloshinskii–Moriya interaction using collective spin-wave dynamics [8].

In propagating SW spectroscopy experiments, two shorted coplanar wavguides (CPWs) are commonly used as a transmitter and a receiver [9]. Each CPW, integrated within the film, consists of a signal line and two ground lines connected at one end. When an rf-current flows through the transmitter, it induces an oscillating magnetic field around the lines that exerts a torque and causes spin precession in the magnetic material beneath. The inverse effect is then used for SW detection by the receiver. Since the generated magnetic field is not homogenous with reference to the film plane and solely...
depends on CPW geometry, it determines the distribution of the SW wavenumber that can be excited.

It is assumed that the transmitter excites a broad spectrum of SW wavevectors of wavenumber $k$ extending to $k_{\text{max}} \approx \frac{\pi}{W}$ ($W$ is a width of CPW line) with a maximum of excitation amplitude approximately around $k_{\text{max,amp}} \approx \frac{\pi}{2W}$ [10]. The question now is: what is the actual wavenumber of the SW with the largest amplitude detected by the receiver situated at a certain distance from the transmitter. While in Brillouin light scattering spectroscopy $k$ is easily accessible, in all electrical spin wave spectroscopic experiments the determination of the SW wavenumber is rather challenging [11].

We aim to answer this question by analyzing our experimental results of SW propagation in yttrium iron garnet (Y$_3$Fe$_5$O$_{12}$, YIG) thin films. YIG films are known for possessing the lowest Gilbert damping parameter, enabling the SW transmission over distances of several hundred micrometers [2, 12]. However, YIG films synthesized by pulsed laser deposition (PLD) exhibit substantially disparate values of anisotropy fields and saturation magnetization, depending on the growth process parameters and, consequently, the stoichiometry of the obtained film [13–15]. It has already been theoretically predicted that anisotropy may significantly affect SW propagation and the transmission characteristics [16, 17]. Therefore, for such YIG films, SW spectra analysis requires careful consideration of the anisotropic properties of a given film.

Here, we compare two methods of experimental determination of the SW wavenumber which include anisotropy fields. The experimental results are then compared with the electromagnetic simulations.

2. Results and discussion

YIG film was grown on a monocrystalline, 111-oriented gadolinium gallium garnet substrate (Gd$_{5}$Ga$_{3}$O$_{12}$, GGG) by means of the PLD technique. The substrate temperature was set to 650 °C and under the 1.2 × 10$^{-4}$ mbar oxygen pressure (8 × 10$^{-8}$ mbar base pressure) the thin film was deposited at the 0.8 nm min$^{-1}$ growth rate using the third harmonic of a Nd:YAG laser ($\lambda = 355$ nm). After the growth, the sample was additionally annealed ex situ at 800 °C for 5 min. X-ray diffraction and reflection measurements showed that the YIG film was single-phase epitaxial with the GGG substrate with the thickness of 82 nm and RMS roughness of 0.8 nm. The XRD $\theta$–$2\theta$ scan, presented in figure 1, clearly shows the high crystallinity of the YIG film, displaying well defined Laue oscillations, typical for highly epitaxial films, which clearly points to the high quality and well textured YIG (111) film [18]. Subsequently, a system of two CPWs made of 100 nm thick aluminum was integrated onto the YIG film (figure 2) using a maskless photolithography technique. The width $W$ of the signal and ground lines was equal to 9.8$\mu$m and the gaps between them were 4$\mu$m wide. The distance between the centers of the signal lines was 150$\mu$m.

To investigate SW propagation, we followed the approach presented in [9] and [12]. Using a vector network analyzer, the transmission signal $S_{21}$ was measured for Damon-Eshbach surface modes with wavevector $k$ perpendicular to the magnetization for magnetic fields ranging from $-310$ Oe to $+310$ Oe (figure 3(a)). Exemplary $S_{21}$ signals (imaginary part), which are shown in figures 3(b) and (c), reveal a series of oscillations as a function of frequency with a Gaussian-like envelope corresponding to the excited SW wavenumber distribution. Figure 3(c) shows that the frequency separation $\Delta f$ between the two oscillation maxima differs noticeably in value depending on the magnetic field. The decrease in signal amplitude is also observed since SW decay length is inversely proportional to the frequency, so that the low-frequency SWs propagate further away [12, 19].

For the frequencies of the highest signal amplitude, the wavenumber $k_{\text{max,amp}}$ can be determined according to the
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A dispersion relation derived for the (1 1 1) crystalline orientation of the YIG film [16, 17]:

\[ f = \frac{\mu_B}{2\pi\hbar} g \left( H + 2\pi M_s k \right) \left( H + \frac{1}{2} H_a - H_a + 4\pi M_s - 2\pi M_s k \right) \]

where \( f \) is the microwave frequency, \( \mu_B \)—the Bohr magneton constant, \( \hbar \)—the reduced Planck constant, \( g \)—the spectroscopic splitting factor, \( H \)—the external magnetic field, \( M_s \)—the saturation magnetization, \( t \)—the film thickness, \( k \)—the wavenumber, \( H_a \)—the cubic anisotropy field and \( H_u \)—the out-of-plane uniaxial anisotropy field. \( H_a = \frac{2K_a}{M_s} \) and \( H_u = \frac{2K_u}{M_s} \), where \( K_a \) and \( K_u \) are anisotropy constants. It should be highlighted that when \( H_a = H_u = 0 \), equation (1) becomes equivalent to the one originally obtained by Damon and Eshbach [20]. The azimuthal angle \( \phi \) defines the in-plane orientation of the magnetization direction with respect to the (1 1 2) axis of the YIG film. In our study, the term \(-\frac{1}{2}(H_a \sin(3\phi))^2\) in equation (1) vanishes since the magnetic field \( H \) is parallel to the (1 1 2) axis and \( \phi = 0^\circ \).

As can be seen from equation (1), in order to determine wavenumber \( k \) one needs to evaluate many material constants,
namely \( g, M_s, t, \Delta H, H_0 \) in the first instance. This problem can be partially solved with a broadband ferromagnetic resonance measurement of the film. For \( k = 0 \) equation (1) simplifies to the formula, which allows for the determination of the spectroscopic factor \( g \) and the effective magnetization

\[
4\pi M_{\text{eff}} = -\frac{1}{2}H_a - H_0 + 4\pi M_s;
\]

\[
f_k = \frac{\mu_B}{2\pi\hbar} \sqrt{H(2\pi M_{\text{eff}}^\ast)}.
\]

Therefore, within this approach, the film thickness and the saturation magnetization should be determined using other experimental methods.

To investigate the ferromagnetic resonance of the YIG film, the reflection signal \( S_{11} \) was measured. In order to avoid an extrinsic contribution to the resonance linewidth caused by non-monochromatic excitation of the CPW \((2\pi\Delta f_{\text{extr}} = v_f\Delta k)\) [21] and, consequently, possible ambiguities in the interpretation of resonance peak position, it is recommended to perform this measurement with the use of a wide CPW. Note that the full width at half maximum of a CPW excitation spectra \( \Delta k \approx k_{\text{max Amp}} \) [21]. In our study we used a CPW with signal and ground lines of the width equal to 450 \( \mu \)m and with the 20 \( \mu \)m wide gaps between them. For such a CPW, the simulated value of \( k_{\text{max Amp}} \) is equal to 49 \( \text{cm}^{-1} \) and, therefore, yields negligible broadening that is of the order of a few MHz.

The measured \( S_{11} \) signal (imaginary part) is depicted in figure 3(a) with the red line. It appears to lie just below the \( S_{21} \) signal. Fitting to the experimental data with equation (2) gave following value of the spectroscopic factor \( g = 2.010 \pm 0.001 \) and the effective magnetization \( M_{\text{eff}}^\ast = 169 \pm 7 \text{ emu cm}^{-3} \). A comparison of \( 4\pi M_{\text{eff}}^\ast \) with \( 4\pi M_s \) (\( M_s = 120 \pm 19 \text{ emu cm}^{-3} \)) was measured using vibrating sample magnetometry) gives \( -\frac{1}{2}H_a - H_0 \) of 616 Oe, showing the substantial difference between the obtained values of \( M_{\text{eff}}^\ast \) and \( M_s \). The determined value of \( -\frac{1}{2}H_a - H_0 \) remains in the midst of the range reported for PLD-grown YIG thin films, from 229 Oe up to 999 Oe [14, 22]. It is worth mentioning that for fully stoichiometric, micrometer-thick YIG films made by means of liquid phase epitaxy (LPE) technique \( -\frac{1}{2}H_a - H_0 = 101 \text{ Oe} \) [14].

Substitution of the \( g, M_{\text{eff}}^\ast, M_s \) and \( t \) values into equation (1) enabled the determination of wavenumber \( k_{\text{max Amp}} = 1980 \pm 102 \text{ cm}^{-1} \). It should be noted that if anisotropy fields were neglected in the equation (1) \( (H_0 = 0) \), yet only saturation magnetization was taken into account, a fitting to the experimental data would not converge. The calculated dispersion relation with the derived value of \( k_{\text{max Amp}} \) assuming \( H_0 = 0 \) is depicted with a blue dashed line in figure 3(a). Omission of anisotropy fields in magnetization dynamic measurements may therefore lead to the significant misinterpretation of the experimental results for the YIG thin films.

Typical values of the cubic magneto-crystalline anisotropy field \( H_a \) range from \(-18 \text{ Oe} \) to \(-64 \text{ Oe} \) for PLD grown YIG films [14, 15, 22], which indicates that resonance measurements, as well as spin wave propagation, are governed by the out-of-plane uniaxial anisotropy. For the film employed in our study, the \( H_a \) value is of about \(-600 \text{ Oe} \), in agreement with previous reports [14, 15, 22]. For any more complex architecture of magnonic waveguides and circuits, it is likewise imperative to investigate the in-plane anisotropy properties [24]. As can be seen from equation (1), one would expect a six fold anisotropy in the plane of \((111)\)-oriented single crystals, which is common among rare-earth substituted YIG garnets and LPE-YIG films [18, 25–27]. To examine this issue, we performed VSM and angular resolved ferromagnetic resonance measurements. Hysteresis loops for all measured in-plane directions exhibit no substantial differences regarding the coercive field \( (\approx 1.2 \text{ Oe}) \), saturation field and saturation magnetization (figure 4(a)). The angular resolved resonance measurements confirm this result and show that the \((111)\) YIG film is isotropic in the film plane (figure 4(b)). The main reason for this behavior is the low

![Figure 4](image-url)
The highest excitation strength is observed for
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The main advantage of extracting the SW wavenumber from $v_g(H)$ dependence is that it does not require additional measurement of $M_s$, which is often notably influenced by an error in the estimated film volume. Since the saturation magnetization $M_s$ can be treated as a fitting parameter in equation (4), the derivation of the SW wavenumber involves only $S_{11}$, $S_{21}$ and thickness measurements. The determined values of $k_{maxAmp} = 1690 \pm 53 \text{ cm}^{-1}$ and $M_s = 116 \pm 2 \text{ emu cm}^{-3}$ remain in a good agreement with that obtained above— ($k_{maxAmp} = 1980 \pm 102 \text{ cm}^{-1}$, $M_s = 120 \pm 19 \text{ emu cm}^{-3}$).

As can be seen from figure 5, SW group velocity attains the maximum value as the magnetic field approaches $H = 0$. The maximum value of $v_g$ is given by:

$$v_g(H=0) \approx \frac{\mu_B}{\hbar} \sqrt{\frac{\pi M_s}{2k} \left( -\frac{1}{2} H_a - H_u + 4\pi M_s[1 - tk] \right)}.$$  \hspace{1cm} (5)$

The zero-field region may therefore become the subject of interest for magnonic applications. Moreover, equation (5) shows that the maximum value of $v_g$ depends on the aniso-
tropy fields. PLD-grown YIG films possessing a high aniso-
tropy would allow for faster information processing in SW
circuits than LPE films for which the value of $-\frac{1}{2} H_a - H_u$ is smaller (as was pointed out above).

To confront our experimental results with the expected, theoretical value of $k_{maxAmp}$, we performed electromagnetic simulations in Comsol Multiphysics. Here, CPW was model
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ance. From the simulated in-plane distribution of the dynamic magnetic field $h_x$ (inset of figure 6), an excitation spectra of CPW was obtained using a discrete Fourier transforma-
tion of $h_x(x)$. The highest excitation strength is observed for $k_{maxAmp} = 1838 \text{ cm}^{-1}$, which corresponds well to the experimentally obtained values within $7\%$ accuracy. The second observed maxima is at $k_2 = 6770 \text{ cm}^{-1}$. However, as its

In figure 5 the derived values of group velocity are shown as a function of the magnetic field. It is found that $v_g$ reaches the value of 7.6 km s$^{-1}$ for the field of 1.3 Oe (preferable in magnonic information processing devices of high efficiency) and 1.4 km s$^{-1}$ for the field of 285 Oe. It should be highlighted that such big differences in $v_g$ values can be further utilized to design tunable, impulse-response delay lines, as $v_g$ changes up to five times with the magnetic field. At a distance of 150 $\mu m$ between CPWs, it would allow us to achieve 20–110 ns delay times of an impulse.

With the red line in figure 5 a fitting is depicted according to:

$$v_g = 2\pi \frac{\partial f}{\partial k} = \frac{\mu_B}{\hbar} \frac{2\pi M_s\left( -\frac{1}{2} H_a - H_u + 4\pi M_s - 4\pi M_s tk \right)}{2\sqrt{(H + 2\pi M_s tk)(H - \frac{1}{2} H_a - H_u + 4\pi M_s - 2\pi M_s tk)}}.$$  \hspace{1cm} (4)$

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value of cubic anisotropy field, which causes the resonance frequency modulation by a value of the fraction of MHz. Such small differences do not surpass the experimental error, nor would they significantly affect the coherent SW propaga-
tion. It is expected that the SW propagation characteristics, measured for any other crystallographic orientation, would therefore remain unaltered.

Another method of extracting the SW wavenumber involves the analysis of the SW group velocity $v_g$. Following [21], $v_g$ can be determined from the frequency difference $\Delta f$ between two oscillation maxima in a $S_{21}$ signal according to the relation:

$$v_g = d \Delta f,$$  \hspace{1cm} (3)$

where $d$ is the distance between two CPWs. To determine $\Delta f$ we chose two neighboring oscillation maxima of the highest $S_{21}$ signal amplitude, as shown in figures 3(b) and (c).

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amplitude is 20 times lower with respect to the amplitude of \( k_{\text{maxAmp}} \); it is not observed in the measured \( S_2 \) signal.

To extend our study, we performed a series of further simulations for the CPW dimensions, which are achievable with electron- and photolithography. We assumed equal widths of signal and ground lines (\( W \)), as well as equal widths of gaps between them (\( G \)). The results are presented in figure 7. It is found that for the widths \( W \) ranging from 300 nm to 40 \( \mu \)m, the wavenumber \( k_{\text{maxAmp}} \) vary between 70 000 \( \text{cm}^{-1} \) and 250 \( \text{cm}^{-1} \), respectively, revealing the CPW wavenumber probing limits. We also note that the gap width significantly affects \( k_{\text{maxAmp}} \). In order to accurately extrapolate its contribution to \( k_{\text{maxAmp}} \), we developed empirical formula which incorporates width \( G \):

\[
\frac{k_{\text{maxAmp}}}{\text{[1/\text{cm}]}^\text{2}} = \frac{2.27}{W + 0.6 G} \tag{6}
\]

The fittings, according to the equation (6), are depicted in figure 7 with solid lines. We found that equation (6) is valid for gap width 0.1 \( W < G < 2 \) \( W \). For \( G = 0.74 \) \( W \) this formula is equivalent to the one previously proposed in [10] \( (k_{\text{maxAmp}} \approx \pi/2W) \).

3. Conclusion

To conclude, we reported on long-range spin wave propagation in a 82 nm thick YIG film over a distance as large as 150 \( \mu \)m. In order to precisely determine the excited wavenumber by the coplanar antenna, it is essential to take into account anisotropy fields present in YIG films. We showed that anisotropy significantly affects SW propagation characteristics; namely it causes an increase in the SW frequency as well as in the SW group velocity. The main contribution comes from the out-of-plane uniaxial anisotropy field. The cubic anisotropy field is negligibly small in the YIG (1 1 1) film and it does not affect magnetization dynamics in the film plane. We explained that the wavenumber determination from group velocity versus magnetic field dependence requires only two types of measurement, which are broadband SW spectroscopy and the measurement of the film thickness.

Acknowledgments

This work was carried out within the Project NANOSPIN PSPB-045/2010 supported by a grant from Switzerland through the Swiss Contribution to the enlarged European Union. J Rychly and J Dubowik would like to acknowledge support from the European Union’s Horizon 2020 MSCA-RISE-2014: Marie Sklodowska-Curie Research and Innovation Staff Exchange (RISE) Grant Agreement No. 644348 (MagIC). The authors would like to thank Professor Maciej Krawczyk for thoughtful suggestions. We also acknowledge valuable comments from Dr Piotr Graczyk and Pawel Gruszecki.

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