Spin wave resonances in $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ films: measurement of spin wave stiffness and anisotropy field

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Abstract

We studied magnetic field dependent microwave absorption in epitaxial $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ films using an X-band Bruker ESR spectrometer. By analyzing angular and temperature dependence of the ferromagnetic and spin-wave resonances we determine spin-wave stiffness and anisotropy field. The spin-wave stiffness as found from the spectrum of the standing spin-wave resonances in thin films is in fair agreement with the results of inelastic neutron scattering studies on a single crystal of the same composition [Vasiliu-Doloc et al., J. Appl. Phys. 83, 7343 (1998)].

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INTRODUCTION

Spin-wave stiffness, $D$, is an important parameter of magnetic materials that characterizes the magnon dispersion law, $\omega = Dk^2$. In the mean-field approximation it is directly related to exchange integral $J$, namely,

$$D = \frac{2JSa^2}{\hbar}$$  \hspace{1cm} (1)

where $\gamma$ is the gyromagnetic ratio, $a$ is the lattice constant, and $S$ is the spin. Inelastic neutron scattering studies of the spin-wave stiffness in manganite single crystals revealed important information on the nature of their ferromagnetic transition. Since this issue is under debate, it is important to study spin-wave stiffness more closely, in particular, to measure $D$ in thin films. It is also important to explore complementary techniques. In principle, spin-wave excitations can be measured using magneto-optical Kerr effect or Brillouin light scattering although existing studies of manganites by these methods do not focus on spin waves.

Spin-wave stiffness has been traditionally measured by the microwave absorption technique: using a fixed frequency ESR spectrometer or broadband techniques. Several groups reported fixed frequency microwave studies of standing spin-wave resonances (SWR) in La$_{0.67}$Ba$_{0.33}$MnO$_3$ (Ref. [14]), and La$_{0.7}$Mn$_{1.3}$O$_3$ (Refs. [15, 16, 17]) thin films. Although spin-wave excitation at microwave frequencies was observed in La$_{0.75}$Sr$_{0.11}$Ca$_{0.14}$MnO$_3$ (Ref. [18]), La$_{0.7}$Ca$_{0.3}$MnO$_3$ (Ref. [19]) and La$_{0.7}$Sr$_{0.3}$MnO$_3$ (Ref. [20]) thin films, it was not studied in detail.

In contrast to inelastic neutron scattering that (i) measures travelling spin waves with large wavevectors, $k \sim 1$-0.1Å$^{-1}$ and (ii) requires large single crystals; the microwave absorption technique measures spectrum of standing spin-wave resonances with small wavevectors, $k \sim 10^{-2} - 10^{-3}$Å$^{-1}$ and operates mostly with thin films. The recent overview of spin-wave excitations in manganites compares thin-film microwave absorption measurements to inelastic neutron scattering studies of single crystals. It turns out that there is no manganite compound that was studied simultaneously by both techniques. Our present work fills this gap. We study spin-wave spectrum in epitaxial La$_{0.7}$Sr$_{0.3}$MnO$_3$ films of different thicknesses and on different substrates by the microwave absorption technique at 9.4 GHz and compare our data to the inelastic neutron scattering studies on single crystals of the same composition.
Consider a thin ferromagnetic film with an "easy-plane" magnetic anisotropy. Magnetic field is oriented at oblique angle $\Psi$ with respect to the film normal. Orientation of magnetization, $\Theta$, is determined by the interplay between the external field, $H$, and the perpendicular anisotropy field, $H_a$, and is found from the following equation:

$$H_a \sin \Theta \cos \Theta = H \sin(\Theta - \Psi)$$

(2)

where in-plane anisotropy has been neglected. In the presence of the microwave magnetic field with frequency $\omega$, whereas $h_{mw} \perp H$, the spin-wave resonances (SWR) are excited. The resonance field $H$ is found from the following condition:

$$\omega^2 = [\gamma H \cos(\Theta - \Psi) - \gamma H_a \cos^2 \Theta + Dk^2]$$

$$\times [\gamma H \cos(\Theta - \Psi) - \gamma H_a \cos 2\Theta + Dk^2]$$

(3)

If surface spins are completely pinned or completely unpinned, then

$$k = \pi n/d$$

(4)

where $d$ is the film thickness and $n$ is an integer. The uniform FMR mode corresponds to $n = 0$, while the spin-wave resonances correspond to $n \neq 0$. For the perpendicular orientation ($\Psi = \Theta = 0$) Eq. (3) yields

$$H_n - H_0 = H_a - \frac{\pi^2 n^2}{\gamma d^2} D$$

(5)

where $H_0 = \frac{\omega}{\gamma}$ and $\omega$ is the microwave frequency. To determine $D$, one measures microwave absorption in dependence of magnetic field and notices a sequence of resonances. By analyzing their spectrum using Eq. (5) one identifies mode numbers $n$. The slope of the linear dependence, $H_n$ vs $n^2$, yields $D$, while the intercept with the $H$-axis yields $H_a$. To enable such procedure the film thickness should lie in certain limits,

$$\delta >> d >> \pi \left[ \frac{D}{\gamma(H_0 + H_a)} \right]^{1/2}$$

(6)

where $\delta$ is the skin-depth. Indeed, for efficient excitation of the spin-wave resonances the film thickness should be smaller than the skin-depth. On the other hand, the film should be thick enough to support several resonances.
EXPERIMENTAL

Our experiments were performed with a bipolar X-band Bruker ESR spectrometer, a \(TE_{102}\) resonant cavity, and an Oxford cryostat. We studied La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) films \((d = 50, 100, 150 \text{ and } 200 \text{ nm})\) grown on the (001) SrTiO\(_3\) substrate (STO), and La\(_{0.67}\)Sr\(_{0.33}\)MnO\(_3\) films \((d = 50 \text{ and } 150 \text{ nm})\) on the NdGaO\(_3\) substrate (NGO). The samples were fabricated by the pulsed laser deposition \[24\] and were cut to small mm-size pieces in order to keep the reasonable value of the cavity \(Q\)-factor. We measured magnetization and resistivity of these films by SQUID magnetometry and four-point technique, correspondingly. The skin-depth at 9.4 GHz estimated from our resistivity measurements \[23\] - 22 \(\mu\)m at 295 K and 5 \(\mu\)m at 50 K- considerably exceeds the film thickness.

The film uniformity could be estimated from the FMR spectrum. A uniform film is characterized by a narrow FMR peak, corresponding to a well-defined anisotropy field, while a nonuniform film usually exhibits a broad FMR peak indicating wide spread of the anisotropy fields. Most part of our samples demonstrated narrow FMR peaks at ambient temperature, although some samples showed several narrow FMR peaks corresponding to discrete values of anisotropy field.

EXPERIMENTAL RESULTS

La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) films on the SrTiO\(_3\) substrate

Figure 1 shows microwave absorption derivative in the perpendicular field for a 200 nm thick La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) film on the SrTiO\(_3\) substrate. We observe a series of slightly asymmetric narrow peaks. The asymmetry arises from the coupling to the dielectric resonances in the STO substrate and was observed in other studies as well. \[20, 23\] The angular dependence of the resonant fields (not shown here) follows Eq. \(5\), hence we attribute these peaks to the spin-wave resonances. We cut the original 5\(\times\)5 mm\(^2\) film to five pieces with the size of 1\(\times\)0.5 mm\(^2\) and all these pieces demonstrated fairly identical spectra. The very fact that we observe sharp and reproducible resonances proves that the film is highly uniform. Another indication of the high quality of the film is the narrow peak-to-peak linewidth (16 Oe at ambient temperature) and low coercive field (11-16 Oe at 295 K).

The mode numbers were established as follows. We assigned consecutive numbers to the
peaks in Fig. 1 and checked whether linear dependence, \( H_n \propto n^2 \), predicted by Eq. (5), holds. The best correspondence to Eq. (3) was achieved for the sequence \( n = 1, 2, 3, \ldots \) or \( n = 0, 2, 3, \ldots \). There is some ambiguity in whether the strongest peak corresponds to \( n = 0 \), to \( n = 1 \) or to their sum, since the splitting between the \( n = 0 \) and the \( n = 1 \) modes as predicted by Eq. (5), is only 25 Oe and this is comparable to the linewidth.

Figure 2 shows SWR intensities and linewidths. The linewidth increases almost linearly with mode number, while intensity decreases. Odd modes have generally higher intensities than even modes (see also Fig. 1).

Figure 3 shows dependence of the resonance fields on the mode number. The higher-order modes obey quadratic dependence, \( H_n \propto n^2 \), while the modes with low \( n \) show tendency to linear spacing that is quite common for the films with surface pinning. We exclude from our analysis the first two modes that should be most strongly affected by surface pinning and determine spin-wave stiffness from the slope of \( H_n \) vs \( n^2 \) dependencies using Eq. (5). The results are shown in Fig. 4.

To find the perpendicular anisotropy field we extrapolate the \( H_n \) vs \( n^2 \) dependencies to \( n = 0 \). Equation (7) and Fig. 3 yield \( H_a = 0.4 \) T at 295 K and \( H_a = 1 \) T at 4.2 K. To analyze these values we note that the perpendicular anisotropy field of a thin film,

\[
H_a = H_{\text{demag}} + H_{\text{cryst}} + H_{\text{stress}},
\]  

(7)

consists of demagnetizing field- \( 4\pi M \), crystalline anisotropy- \( H_{\text{cryst}} \), and stress-induced anisotropy- \( H_{\text{stress}} \). The crystalline anisotropy of La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) is very small \([26, 27]\) and does not exceed 0.03 T. \([28]\) Demagnetization field as estimated from magnetization \([26, 27]\) is \( H_{\text{demag}} = 0.74 \) T at 4.2 K. Since the lattice mismatch between La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) and SrTiO\(_3\) is only 1.4 % and the film is sufficiently thick, the \( H_{\text{stress}} \) is not high and achieves considerable magnitude only at low temperatures. \([29]\) Equation (7) yields the stress anisotropy field, \( H_{\text{stress}} = 0.26 \) T at 4.2 K. This means that even at low temperatures the demagnetization field is the dominant contribution to the anisotropy field. This is consistent with other measurements. Indeed, magnetization studies of the Ref. \([27]\) for the films of comparable thickness found that \( H_{\text{demag}} = 0.8H_a \) at 10 K, while Ref. \([26]\) found that \( H_{\text{demag}} = 0.95H_a \) at 295 K.
La$_{0.67}$Sr$_{0.33}$MnO$_3$ films on the NdGaO$_3$ substrate

Figure 5 shows microwave absorption spectrum for a 150 nm thick La$_{0.67}$Sr$_{0.33}$MnO$_3$ film on the NdGaO$_3$ substrate at 108 K. We observe a strong and narrow peak at 10445 Oe and a series of low-field satellites. The peak-to-peak linewidth of the dominant resonance is very small (12 Oe at ambient temperature and 33 Oe at 108 K) and this proves high quality of the film. The coercive field at ambient temperature is only 4 Oe. We cut the film to several pieces and they showed consistent spectra.

To identify the resonances we measured temperature and angular dependencies of the resonant field and came to conclusion that the peaks designated with integer numbers in Fig. 5 are spin-wave satellites of the peak at 10445 Oe, while the strong peak at $H = 7470$ Oe does not belong to this series. Indeed, the angular dependencies of resonant field of the numbered peaks are very similar (not shown here) and different from that for the peak at 7470 Oe. The same is true with respect to the temperature dependencies. We attribute the peak at 7470 Oe to the region with a different discrete value of the anisotropy field and exclude it from the subsequent analysis.

Figure 6 shows that the resonant fields of higher modes follow $H_n \propto n^2$ dependence. The slope of this dependence (the first mode excluded) yields the spin-wave stiffness $D$. The results are plotted in Fig. 4. The same data yield the perpendicular anisotropy field. We find $H_a = 0.73$ T at 4.2 K. This is almost equal to the demagnetizing field, $4\pi M = 0.74$ T, and means that the stress-induced anisotropy is negligible here, as expected for the lattice-matched substrate. The linewidth (see inset) steadily increases with $n$.

Other films

We observed spin-wave resonances in several films with different thickness. In a very thin ($d = 50$ nm) La$_{0.67}$Sr$_{0.33}$MnO$_3$ film on SrTiO$_3$ we observed only one spin-wave resonance which was displaced down by 0.23 T from the dominant FMR resonance [while Eq. (5) predicts 0.08 T]. Such pronounced displacement is obviously related to strong surface pinning, hence it is not possible to measure $D$ there. In several 150 nm thick La$_{0.67}$Sr$_{0.33}$MnO$_3$ films on SrTiO$_3$ we observed two overlapping series of spin-wave resonances, so that determination of $D$ here was ambiguous. Ref. [17] observed such split spin-wave resonances in a 350
nm thick $\text{La}_{0.7}\text{Mn}_{1.3}\text{O}_3$ film on $\text{LaAlO}_3$ substrate and showed that the splitting disappears after annealing in oxygen. Following Ref. [17] we studied the effect of oxygen annealing on the SWR spectra in our films. Contrary to Ref. [17] we found that oxygen annealing at different temperatures from $600^\circ\text{C}$ to $900^\circ\text{C}$ does not ameliorate the SWR spectrum in our films but introduces additional splitting. In particular, the resonant peaks in annealed films split into many narrow lines with the spacing of $\sim15\text{ Oe}$. The difference between our results and those of Ref. [17] is probably related to the fact that we operate with the film of different composition and on different substrate.

**DISCUSSION**

*Zero-temperature spin-wave stiffness*

Figure 4 compares the spin-wave stiffness found in our microwave absorption studies of $\text{La}_{0.7}\text{Sr}_{0.3}\text{Mn}_{0.7}\text{O}_3$ thin films to inelastic neutron scattering measurements on single crystals of the same composition.[3, 4, 5] Consider first the limit $T = 0$. Our measurements for two films of different thickness yield $D_0^{\text{film}} = 210\text{ meV }\AA^2$ while the corresponding neutron scattering data show lower values, $D_0^{\text{cryst}} = 188$ (Ref. [3]), 170 (Ref. [2]), 176 (Ref. [4]), and 190 meV $\AA^2$ (Ref. [5]). The discrepancy between $D_0^{\text{film}}$ and $D_0^{\text{cryst}}$ may arise from the fact that few atomic layers adjacent to the film-substrate interface are nonmagnetic. In LSMO this ”dead layer” may be up to 5 nm thick,[30, 31] hence ”magnetic” thickness that appears in Eq. (5) is smaller than the nominal thickness. The correction for the ”dead layer” can bring down $D_0^{\text{film}}$ by 5%.

The spin-wave stiffness at $T = 0$ can be also estimated from the temperature dependence of magnetization and the $T^2$-Bloch law (see also Ref. [32]). For the $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ single crystals this yields $D_0^{\text{Bloch}} = 154$ (Ref. [33]), while for ceramics of the same composition, $D_0^{\text{Bloch}} = 197\text{ meV }\AA^2$ (Ref. [34]).

*Temperature-dependence*

Consider now the temperature dependence of the spin-wave stiffness. Figure 4 shows that the results for two films with different thicknesses and on different substrates (one with tensile stress-STO and another with a weak compressive stress-NGO) are very close,
as expected for intrinsic property. At ambient temperature, we find for these two films $D_{\text{film}}=104$ and 114 meV Å$^2$, correspondingly. This is almost identical to the single crystal data at ambient temperature- $D_{\text{cryst}}=114$ (Ref. [3]) and 100 meV Å$^2$ (Ref. [4]). However, one should take into account the difference in $T_C$ as well.

Comparison between the samples

In order to compare data for the samples with different $T_C$ we consider $D(T)$ vs $M(T)$ plots where the temperature is an implicit variable. A similar plot was used earlier by Ref. [35] to compare spin-wave stiffness of the Fe-Cr alloys with different composition and different $T_C$. The rationale behind such plot is the mean-field expression -Eq. (1)- that in fact relates the spin-wave stiffness to magnetization, $M = g\mu_B S/V_a$. Here, $\mu_B$ is the Bohr magneton, $g$ is the $g$-factor, and $V_a \propto a^3$ is the atomic volume. Equation (1) yields direct proportionality, $D \propto J M a$. Strictly speaking, this proportionality is expected only for the Heisenberg model and at $T = 0$. However, since $M$ and $D$ both go to zero at $T_C$, while $J$, in general, varies continuously across the ferromagnetic transition; then we expect that the $D \propto M$ proportionality holds up to $T_C$. Indeed, as the Ref. [36] shows, empirical data on many ferromagnetic compounds suggest that $D$ and $M$ have the same temperature dependence in the whole range from $T = 0$ to $T = T_C$.

To effectuate this approach we plot $D$ vs $M$ (Fig. 7) where $D$ and $M$ are measured at the same temperature. [37] We find $D$ from the microwave absorption spectra, while the magnetization is estimated indirectly, from the anisotropy field, $H_a$. Indeed, since the dominant contribution to $H_a$ in our films is the demagnetizing field $4\pi M$ (especially for the films on NGO), hence the anisotropy field is a measure of magnetization.

Figure 7 plots the spin-wave stiffness versus anisotropy field where the temperature is an implicit parameter. It also plots the corresponding single crystal neutron-scattering data of Ref. [4] where magnetization was estimated from the intensity of the electronic Bragg peak. The upper horizontal scale in Fig. 7 was chosen in such a way that the low-temperature limit of the electronic Bragg peak intensity ($\Delta I_B = 1.85 \times 10^4$) corresponds to saturation magnetization of La$_{0.7}$Sr$_{0.3}$MnO$_3$, i.e. $4\pi M = 0.74$ T. The horizontal error bars in our thin film measurements take into account the possible difference between the anisotropy field and magnetization arising from the stress anisotropy field [Eq. (7)]. We assume extreme values
of $H_{\text{stress}}/4\pi M = -0.06$ and 0.2 for the films on NGO and STO, correspondingly.

We observe that above $T = 295$ K the data for both our films and for the single crystal collapse. The resulting $D(M)$ dependence is quasilinear that indicates the same critical indices of $D$ and $M$ at $T_C$. This is not obvious since the neutron-scattering measurement were performed in zero magnetic field while the microwave measurements were performed in finite field of 0.4 T to 1 T. Using Eq. (11) we find the same value of the exchange integral, $J = 3.6$ meV (for $S = 1.85$ and $a = 3.88\AA$) for the film and single crystal. This is also not obvious since thin films are strained.

We processed in the same way the microwave absorption data of Ref. [15, 16] for the film of different composition -La$_{0.7}$Mn$_{1.3}$O$_3$ (see inset in Fig. 7). While $D(M)$ proportionality holds at low temperatures, there is an upward deviation as $T \rightarrow T_C$. This suggests discontinuous variation of $D$ across the ferromagnetic transition. Our data for the La$_{0.7}$Sr$_{0.3}$MnO$_3$ films do not indicate such discontinuity.

**Linewidth**

The linewidth that steadily increases with mode number (Figs. 2, 6) is not frequently observed in microwave absorption studies of spin-wave resonances. Previous studies of permalloy films and other highly conducting ferromagnets found weak and nonmonotonous dependence $\Delta H(n)$. (Refs. [38, 39, 40, 41, 42]) Such nonmonotonous dependence arises from the sum of several sources such as eddy-current damping, surface roughness, and fluctuations (exchange energy, anisotropy field, thickness). [43]

The $k$-dependent linewidth observed in our studies could be hardly intrinsic. Indeed, theoretical prediction for the magnon-magnon scattering in manganites yields inverse spin lifetime $\Gamma \propto k^4$ (Ref. [44]). The neutron scattering studies of La$_{0.85}$Sr$_{0.15}$MnO$_3$ single crystals indeed yield $\Gamma = 3050k^4$ (here $k$ is in $\text{Å}^{-1}$ and $\Gamma$ is in meV). Extrapolation of this $k^4$ dependence (obtained for 10 K and $k = 0.02-0.16\text{Å}^{-1}$) down to the range of wavevectors occurring in our microwave studies ($k_{\text{max}} = 0.014\text{Å}^{-1}$) yields $\Gamma = 1.1 \times 10^{-4}$. This is much smaller than what we observe in Fig. 2: $\Gamma = \Delta H/\gamma = 4.7 \times 10^{-3}$ (note however that our films have different composition as compared to those studied in Ref. [6]). This indicates that the $k$- dependent linewidth found in our studies in thin films is extrinsic. It most probably arises either from the inhomogeneous broadening associated with thickness nonuniformity,
or from the spin-wave scattering on surface and bulk disorder. If we take an extreme approach and assume only thickness nonuniformity, then Ref. yields
\[ \Delta H_d = \Delta H_0 + \frac{2D\pi^2n^2}{d^3} \Delta d, \] (8)
where \( \Delta H_0 \) is the linewidth of the uniform precession mode and \( \Delta d \) is the average thickness variation. Analysis of our data according to Eq. (8) (dashed lines in Figs. 2,6) yields \( \Delta d = 4 \text{ nm (2\%)} \) and \( 6 \text{ nm (4\%)} \) for the films on STO and on NGO, correspondingly.

If we go to another extreme and assume spin-wave scattering to be the only source of line broadening, then according to the transit-time treatment \[ \Delta H_{sc} = \Delta H_0 \] we find
\[ \Delta H_{sc} - \Delta H_0 = \frac{v_g}{\gamma l_{sw}} = \frac{2D\pi n}{\gamma d l_{sw}} \] (9)
where \( v_g = 2Dk \) is the group velocity and \( l_{sw} \) is the mean free path. Spin-wave scattering on bulk disorder is characterized by the combination of linear and quadratic \( k \)-dependence, whereas the linear \( k \)-dependence implies constant mean free path. Analysis of our data according to Eq. (9) and assuming constant \( l_{sw} \), yields \( l_{sw}/d = 2 \) for the LSMO/STO film at ambient temperature (Fig. 2). For the LSMO/NGO film (Fig. 6) we find \( l_{sw}/d = 1.4 \) and 1.3 at 108 K and at 187 K, correspondingly. The spin-wave mean-free-path being on the order of film thickness, suggests that the scattering occurs predominantly at film interfaces. Such scattering may result from surface roughness or from the localized Mn\(^{4+}\)-ions or Mn\(^{2+}\)-ions at film surface.

The observed \( k \)-dependence of the linewidth is most probably due to both mechanisms: thickness nonuniformity and scattering. Note however, that both extreme approaches [Eq. (8) and Eq. (9)] yield long mean free path that practically excludes bulk scattering. This is surprising, since the stoichiometry of La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) suggests two possible states of Mn-ion: Mn\(^{3+}\) with spin \( S=3/2 \) and Mn\(^{4+}\) with spin \( S=2 \). If La\(_{0.7}\)Sr\(_{0.3}\)MnO\(_3\) were Heisenberg ferromagnet this would certainly result in magnetic inhomogeneity. However, observation of standing spin-wave resonances with high mode numbers indicates negligible bulk scattering and a single magnetic state of Mn-ions in the bulk, as was already established by the NMR studies of Mn\(^{55}\) in La\(_{0.67}\)Sr\(_{0.63}\)MnO\(_3\) (Ref. 31).
Other manganite compounds

The standing spin-wave resonances have been observed so far in the manganite compounds of the general formula La$_{1-x}$A$_x$MnO$_3$ where A is Sr,Ca,Ba,Mn and $x \sim 0.3$ (Refs. [14, 15, 16, 17, 18, 19, 20] and present work). The $x \sim 0.3$ composition corresponds to highest conductivity and is the most distant from phase boundaries, in other words, the phase separation effects should be least insignificant here. This composition has also the highest spin-wave stiffness [5, 21] that indicates increased length of the exchange interaction. The very fact that so far there is no indication of the standing spin-wave resonances in manganite compounds with $x \neq 0.3$ (we also didn’t find any spin-wave resonances in La$_{0.8}$Sr$_{0.2}$MnO$_3$ films) may serve as an indirect evidence of strong spin-wave scattering there.

CONCLUSIONS

We measured temperature dependence of the spin-wave stiffness in thin La$_{0.7}$Sr$_{0.3}$MnO$_3$ films as determined from the standing spin-wave resonances at microwave frequencies. At ambient temperature, the spin-wave stiffness of thin films and of single crystals is the same, while at low temperatures the spin-wave stiffness of thin films is enhanced with respect to that of a single crystal.

The spin-wave linewidth in our films is limited by the scattering at film interfaces. The very fact that we are able to observe spin-wave resonance in La$_{0.7}$Sr$_{0.3}$MnO$_3$ up to eighth order implies high degree of coherence and very low bulk spin-wave scattering. This is important for spintronics and means that La$_{0.7}$Sr$_{0.3}$MnO$_3$ can be used as a spin conserving component.

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in some experimental runs we slowly heated the sample from low temperature and measured
the spectra in a continuous way without waiting for thermalization. In such experiments we
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FIG. 1: Absorption derivative spectrum for a 200 nm thick $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ film on the SrTiO$_3$
substrate in the perpendicular magnetic field. The mode number is shown at each peak. The
microwave frequency is 9.4 GHz, the incident power is $P_{mw} = 0.2$ mW (-30 dB), the modulation
field is 10 Oe.

FIG. 2: The filled symbols indicate the SWR linewidth, $\Delta H_n$, the red solid line shows linear fit [Eq. (9)], and the red dashed line shows quadratic fit [Eq. (8)]. The open symbols indicate integrated
SWR intensity corrected for the linewidth, $I = I_{pp}(\Delta H)^2$. Here, $I_{pp}$ is the peak-to-peak magnitude
of the absorption derivative. The black solid line here is the guide to the eye, the dashed black
line shows Kittel’s $1/n^2$ prediction [1]. The sample is a 200 nm thick $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ film on the
SrTiO$_3$ substrate at ambient temperature.
FIG. 3: The resonance field of different modes for the film shown in Fig. 1. Filled symbols indicate the data measured at fixed and known temperatures and at low microwave power, $P_{mw} = 0.2$ mW. Open symbols indicate the data measured at ambient temperature and increased microwave power (62.5 mW and 200 mW, correspondingly). Here, the sample temperature is higher than the ambient temperature due to self-heating. The lines show $H_n \propto n^2$ approximation.

FIG. 4: Temperature dependence of the spin-wave stiffness $D(T)$. The circles stand for our microwave measurements on thin films on substrate. The squares show inelastic neutron scattering data for the La$_{0.7}$Sr$_{0.3}$MnO$_3$ single crystals. The triangles stand for the $D^{Bloch}(T = 0)$ estimated from the temperature dependence of magnetization and $T^{3/2}$-Bloch law. The lines are the guide to the eye.

FIG. 5: Absorption derivative spectrum for a 150 nm thick La$_{0.67}$Sr$_{0.33}$MnO$_3$ film on the NdGaO$_3$ substrate. The mode number is shown at each peak. A strong peak at $H = 7470$ Oe originates from the ferromagnetic resonance in a region of the film with the different anisotropy field.

FIG. 6: Resonance field of the SWR modes at several temperatures for the sample shown in Fig. 5. The lines show $H_n \propto n^2$ approximation. The inset shows linewidth vs mode number. The dashed lines in the inset show quadratic approximation [Eq. (8)].

FIG. 7: Spin-wave stiffness versus magnetization at varying temperature. The circles stand for our microwave measurements on thin films. As a measure of magnetization we take the perpendicular anisotropy field, $H_a$ (lower horizontal scale). The squares stand for the single crystal data measured by the inelastic neutron scattering technique (Ref. 14). As a measure of magnetization in this case we take the integrated intensity of the electronic Bragg peak (upper horizontal scale). The dashed line shows linear approximation. The inset shows similar $D(M)$ dependence for the La$_{0.7}$Mn$_{1.3}$O$_3$ film as extracted from the microwave absorption measurements of Ref. 15, 16.
Fig. 1
Fig. 2
Fig. 3

The figure shows a graph of $H$ (in Oe) plotted against $n^2$, with data points for temperatures of 221 K, 270 K, 289 K, and 289 K. The graph includes a legend indicating the temperatures for the different data sets.

The graph is labeled 'LSMO/STO' at the top right corner.
Fig. 4
Fig. 5

The figure shows a graph of $\frac{dP}{dH}$ (arb. units) vs. $H$ (Oe) at 108 K. The graph displays a spurious phase indicated by a peak labeled as 1. The data is presented with a scale of $10^5$ and $10^6$ for $dP/dH$. The data points for LSMO/NGO are marked with red numbers 1, 2, 3, 4, 5, and 6, with the graph showing significant variations in $dP/dH$ across the range of $H$ values from 7000 to 10000 Oe.
Fig. 6
Fig. 7