Differences in the magnon diffusion length for electrically and thermally driven magnon currents in Y$_3$Fe$_5$O$_{12}$

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Abstract

Recent demonstration of efficient transport and manipulation of spin information by magnon currents have opened exciting prospects for processing information in devices. Magnon currents can be excited both electrically and thermally, even in magnetic insulators, by applying charge currents in an adjacent metal layer. Earlier reports in thin yttrium iron garnet (YIG) films suggested that the diffusion length of magnons is independent on the excitation method, but different values were obtained in thicker films. Here, we study the magnon diffusion length for electrically and thermally excited magnons in a 2-µm-thick YIG film as a function of temperature and magnetic field. Our results evidence that the diffusion length depends on the generation mechanism, suggesting that magnons of different energies are excited -sub-thermal and thermal magnons for electrically and thermally driven magnon currents, respectively- and, consequently, indicating that the magnon diffusivity is frequency dependent. Moreover, we show that the damping of the thermally driven magnons with magnetic field is weaker than for those excited electrically. Finally, we demonstrate that the magnon diffusion length for thermally excited magnons is independent of the YIG thickness and material growth conditions, confirming that this quantity is an intrinsic parameter of YIG.

I. Introduction

Insulator-based spintronics is nowadays one of the most promising fields to transport and manipulate spin information, which in magnetic insulators (MIs) is carried by magnons [1–20] instead of conduction electrons in non-magnetic conductors [21]. A magnon is a quasiparticle corresponding to a collective magnetic-moment precession that carries a spin angular momentum in materials with magnetic ordering, i.e., a quantized spin wave. The possibility of transporting spin information over long distances using magnons [4,9,16], combined with the fact that the use of MIs prevents both the emergence of spurious transport effects due to charge flow in the ferromagnet and unnecessary Ohmic losses, make MIs very attractive materials for spintronic applications with potential to compete with their metallic counterparts.

Magnon spin currents in MIs can be generated either by ferromagnetic resonance [9,10] (low-frequency coherent magnons), by inducing a thermal gradient [16] (high-frequency incoherent magnons), or by electrical means by making use of the spin Hall effect (SHE) of heavy metals such as Pt [4] (high-frequency incoherent magnons), whereas, in most of the cases, have been detected electrically by employing the inverse spin Hall effect (ISHE). In the original work of Cornelissen et. al. [4], magnons were electrically and
thermally excited in the magnetic insulator yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG), and electrically detected up to tens of micrometers apart at room temperature, by employing a non-local configuration in which Pt strips acted as injectors and detectors of the magnon currents. Many studies on incoherent magnon spin transport have followed [1,3–7,11,14–19,22], in which YIG played the central role because of its soft ferrimagnetism, negligible magnetic anisotropy, and low Gilbert damping [1,3–7,9,11,16,18,19,23], albeit magnon spin transport has also been demonstrated in other MIs [12,24,25].

The key parameter that defines the characteristic length to which magnons propagate is the magnon diffusion length ($\lambda_m$). Its value has been studied in YIG as a function of temperature [5,6,11,24], magnetic field [18], thermal gradient [16], and thickness [3]. Earlier reports suggested that $\lambda_m$ is the same regardless of the mechanism by which the magnons are excited (by thermal gradients or by torques employing the SHE) [5], but more recent works showed that those values might be different [3,11]. It is thus not clear whether the thickness of the MI layer might play a role on the value of $\lambda_m$ or whether the nature of the excited magnons, and thus their diffusivity, might be different due to the different energy scales involved in the two types of excitation methods.

In this paper, by employing a non-local configuration, we report a systematic temperature and magnetic field dependence study of the magnon diffusion length in 2-µm-thick YIG films for electrically and thermally excited magnons. Our results evidence that the diffusive transport of magnons depends on the way they are excited, supporting the idea that magnons of different energies, which exhibit different characteristic diffusive length scales, are generated. Furthermore, we demonstrate that the size and temperature dependence of the magnon diffusion length of the thermally excited magnons are the same regardless of the YIG thickness and growth method. This result shows the robustness of thermally induced magnon transport to extract the magnon transport properties of YIG and, by extension, of MIs.

II. Experimental details

The devices were fabricated on top of 2-µm-thick YIG films provided by Innovent e.V. (Jena, Germany). YIG was grown by liquid phase epitaxy (LPE) in a (111) gadolinium gallium garnet (Gd$_3$Ga$_5$O$_{12}$, GGG) substrate. In a first sample (sample 1), a 5-µm-thick Pt layer was magnetron-sputtered ex situ (80 W; 3 mtorr of Ar) on top of YIG, and Pt strips (width $w = 450$ nm, length $L = 80$ µm) were patterned by negative e-beam lithography and Ar-ion milling with different edge-to-edge distances ($d = 1–20$ µm). In a second sample (sample 2), devices with distances ranging from 8.5 µm to 125 µm were fabricated. In this case, for shorter distance devices ($d = 8.5-40$ µm), the Pt strip dimensions are the same as for sample 1, whereas for longer distances ($d = 50-125$ µm), the dimensions are $L = 650$ µm and $w = 2.7$ µm and the measured voltage is normalized accordingly [4]. A scanning electron microscopy (SEM) image of one of the devices is shown in Fig. 1(a).

Magnetotransport measurements were carried out in a liquid-He cryostat at temperatures $T$ between 10 and 300 K, externally applied magnetic fields $H$ up to 9 T, and a 360º in-plane sample rotation. We use a non-local configuration, where we apply a DC current $I$ along a Pt strip (injector) while we measure the voltage along an adjacent Pt strip (detector). In order to separate the electrically generated non-local voltage from the thermally generated one, the polarity of the DC current is reversed at the injector. The
difference of the non-local voltage, \( V_{NL}^e = \frac{[V_{NL}(+I) - V_{NL}(-I)]}{2} \), corresponds to the electrical signal (equivalent to the 1\textsuperscript{st} harmonic signal when using an AC measurement), whereas the sum, \( V_{NL}^t = \frac{[V_{NL}(+I) + V_{NL}(-I)]}{2} \), corresponds to the thermally driven signal (equivalent to the 2\textsuperscript{nd} harmonic signal) [7,26,27].

![Diagram](image)

FIG. 1. (a) SEM image of a non-local device used in this work \((d = 6 \mu m)\). The measurement configuration and the geometrical parameters are indicated. (b,c) Schematic representation of the creation, transport and detection of magnon currents in the non-local devices by means of (b) electrical excitation and (c) thermal excitation. (d,e) Representative angular-dependent non-local signals detected for (d) electrically and (e) thermally excited magnons using the measurement configuration shown in (a). The magnetic field applied is \( H = 0.03 \ T \), which is sufficient to saturate the magnetization of our YIG films. The measurement temperature is 100 K and the device corresponds to sample 1. The non-local signals are presented as the non-local voltage normalized to the applied current in (d) and to the square of the applied current in (e), showing that \( V_{NL}^e \) and \( V_{NL}^t \) are linear and quadratically dependent on the injected current, respectively.

III. Results and Discussion

A. Angular dependence of the non-local signal for electrically and thermally excited magnons.

We investigate the magnon spin transport for both electrically and thermally induced magnon currents in YIG by employing the non-local configuration shown in Fig. 1(a). This device scheme allows exploiting the large SHE in Pt \([28–31]\) to electrically excite
and detect magnon currents in YIG. By applying a charge current along a Pt strip, a spin accumulation is induced at the Pt side of the Pt/YIG interface due to the SHE [which is in the plane of the film and perpendicular to the current, see vector notation in Fig. 1(b)]. When the YIG magnetization and spin polarization of the spin accumulation in Pt are parallel (antiparallel), a magnon is annihilated (created) due to exchange interaction between the Pt electron spins and the YIG magnetic moments, leading to a magnon imbalance that modifies the magnon chemical potential close to the interface [13]. This gives rise to a diffusion of magnons (magnon spin current) that can propagate for several microns along YIG [4,5,7,14,15,17–19]. By the reciprocal process, a second Pt strip can detect the magnon imbalance, as the induced spin accumulation in Pt (due to the magnon-to-spin conversion at the interface) is finally converted to a voltage by the ISHE [10]. Given that the electrical excitation of magnon currents is a linear process (for weak and moderate excitation amplitudes) [4,32], the detected non-local voltage $V_{NL}$ (see section II for details) is proportional to the applied charge current. This is indeed confirmed in our devices for all experimental conditions reported in this work. As an example, we show in Fig. 1(d) the non-local $V_e$ signal measured in a representative device at two different currents while rotating the in-plane magnetic field. The two curves nicely overlap once the signal is normalized by the injected current. Moreover, note that the angular dependence of the non-local voltage shows the expected $\sin^2$ dependence, which is due to the symmetry of the SHE and the ISHE at the injector and detector Pt stripes, respectively, and their relative orientation with the magnetization of the YIG layer [4,7,19].

On the other hand, magnons can also be thermally excited. In ferromagnetic materials, a thermal gradient drives a magnon spin current parallel to the induced heating flow due to the spin Seebeck effect [33]. Therefore, by making use of the Joule dissipation in a Pt stripe, a thermal gradient can be generated in the YIG film beneath, resulting in a diffusive magnon current that can be non-locally detected by employing the ISHE of a second Pt strip (Fig. 1c) [1,3–6,11,16]. In this non-local spin Seebeck configuration, the voltage $V_{NL}^{th}$ (see section II for details) scales quadratically with the applied charge current. This is confirmed in our devices at temperatures above 2.5 K and for the whole range of currents employed in this work. This dependence is demonstrated in Fig. 1(e), where we show the angular dependence of the non-local voltage $V_{NL}^{th}$ measured at two different currents in a representative device, which coincide once we normalize the curves to the square of the injected current. At 2.5 K, and for low current densities, however, $V_{NL}^{th}$ does not scale with the square of the current (see appendix A), which is consistent with previous reports [34]. The angular dependence of the thermally excited magnon currents shows a $\sin$ dependence with $\alpha$ [see Figs. 1(a) and 1(e)], because in this case only the ISHE symmetry of the detector plays a role [4,7].

From these two types of non-local signals, and by measuring their amplitude in devices having different distances $d$ between the injector and detector stripes, we can extract the magnon spin diffusion length of our YIG films.

**B. Temperature and magnetic-field dependence of the non-local signals.**

We now investigate the temperature- and magnetic field-dependence of the magnon transport for both thermally and electrically excited magnon currents. The temperature dependence of the amplitude of the non-local signal, measured at $H = 0.03$ T and for
different distances between the Pt electrodes, is plotted in Figs. 2(a) (for electrically excited magnons) and 2(b) (for thermally excited magnons).

The non-local signal for electrically excited magnons [Fig. 2(a)] vanishes when approaching zero temperature and, for the longest distances, can only be extracted reliably above 50 K (see appendix B). The signal increases with increasing temperature, having a maximum at approximately 100 K. This behavior, which is in agreement with Refs. [5,7], can be understood by taking into account that the magnon population is strictly zero at zero temperature and increases with temperature, leading to a more efficient generation. However, above 100 K, the non-local signal decreases up to 300 K. This temperature dependence is different than the ones reported in Refs. [5,7], but closely resembles the temperature dependence of the spin Hall magnetoresistance (SMR) measured in our Pt/YIG bilayers (see Appendix B). This correlation is expected as the amplitude of both the SMR and the non-local signal have the same dependence with the spin Hall efficiency at the Pt/YIG interface [13]. Besides, as expected, the non-local signal decreases when the distance between the Pt electrodes increases.

![Graphs](image-url)

**FIG. 2.** (a-b) Temperature dependence of the non-local voltage amplitude for (a) electrically and (b) thermally excited magnons at 0.03 T, and for different distances between the injector and detector Pt stripes. (c-d) Magnetic field dependence of the non-local voltage amplitude measured at a distance of 4 µm and different temperatures for (c) electrically and (d) thermally excited magnon currents. The non-local signal is normalized to the charge current applied (150 µA) in (a) and (c), and to the square of the current in (b) and (d). All data correspond to sample 1.

In the case of thermally excited magnons [Fig. 2(b)], the largest non-local spin Seebeck signal is found at the lowest temperature (2.5 K). The signal is larger than the one measured for electrically-driven magnon currents and, for this reason, we are able to
detect non-local signals for longer distances (~20 μm in this sample, and up to 125 μm in the second sample with longer distances, see Appendix C). The amplitude sharply decreases between 2.5 K and 10 K, followed by a plateau between 10 and 50 K, and finally decreases monotonically with increasing temperature. The low temperature behavior (T < 10 K) could be related to the strong variation of the thermal gradient generated at the Pt injector, since many of the parameters defining the thermal gradient (such as thermal conductivity and specific heat of YIG) have a strong temperature dependence at this low temperature regime [35]. Indeed, a puzzling behavior of the non-local spin Seebeck effect signal have been reported at this temperature range, whose origin remains unclear [5,11]. Moreover, and in agreement with what is observed for electrically-driven magnons, the signal gets smaller when increasing the injector-detector distance. Finally, a sign change of the non-local spin Seebeck effect is expected for injector-detector distances that are below certain value (which is on the order of the YIG thickness) [1,3,20]. In our case, however, we do not observe this behavior as all measurements are taken above the distance at which the sign change occurs.

The magnetic field dependence of the non-local signal is plotted in Figs. 2(c) (for electrically excited magnons) and 2(d) (for thermally excited magnons) for a distance d = 4 μm between the Pt electrodes and different temperatures. The non-local signal for electrically excited magnons [Fig. 2(c)] decreases monotonously with magnetic field, being strongly reduced at 9 T. In contrast, the signal for thermally excited magnons [Fig. 2(d)] shows a shallow maximum at ~1 T, and slowly decreases to 9 T. These behaviors are similar to the ones reported in Ref. [18].

C. Temperature and magnetic field dependence of the magnon diffusion length.

From the data reported in the previous section, we can now extract the magnon diffusion length at different magnetic fields and temperatures, which is the relevant parameter that describes the magnon transport behavior. As an example, we show in Figs. 3(a) and 3(b) the non-local signals as a function of the distance d between the Pt electrodes for a particular temperature (150 K) and selected magnetic fields (0.03, 5 and 9 T). We identify two distinctive regions known as the diffusion regime (light purple region) and the exponential regime (light brown region). In the diffusion regime, which corresponds to \(d < \lambda_m\), the non-equilibrium magnon accumulation diffuses away from the injector into the YIG with a geometrical decay [13,22,24]. Further away, at \(d \approx \lambda_m\), magnons relax showing an exponential decay for the two type of excited magnons [3,4,11]. Therefore, in order to determine \(\lambda_m\), a linear fitting of the natural logarithm of the non-local voltage amplitude is performed in the exponential regime, as shown in Figs. 3(a) and 3(b) (red solid lines). In the case of the thermally excited magnons, the linear fittings should be carried out for distances shorter than 3–5 times \(\lambda_m\) to avoid entering the \(1/d^2\)–regime, where the signal is dominated by the temperature gradient induced (by geometric thermal diffusion) at the YIG/GGG interface underneath the Pt detector [11]. From these fittings, we extracted the magnon diffusion length for both electrically (\(\lambda_m^e\)) and thermally excited magnons (\(\lambda_m^{th}\)) at different temperatures and applied magnetic fields. The results are presented in Figs. 3(c)-3(f).

At any magnetic field applied, \(\lambda_m^e\) shows a constant or slightly decreasing behavior with increasing temperature [Fig. 3(c)]. As discussed above, we cannot estimate \(\lambda_m^{th}\) below 50 K because of the small signal-to-noise ratio. \(\lambda_m^e\) decreases monotonously with increasing the magnetic field [Fig. 3(e)], in line with the strong decay reported in Ref. [18] for
electrically excited magnons at 300 K. Both the temperature and field dependences are completely different for $\lambda_m^{th}$ [Fig. 3(d)]. At low magnetic fields (0.03 T), $\lambda_m^{th}$ is maximum at the lowest measured temperature (2.5 K) and decreases up to 30 K. In this temperature range, the increase of the magnetic field reduces the value of $\lambda_m^{th}$, although the same trend with temperature is kept in the whole range of magnetic fields explored (up to 9 T). For temperatures above 30 K, however, two different temperature dependences for $\lambda_m^{th}$ are identified depending on the strength of the magnetic field: i) at low magnetic fields (0.03 T), $\lambda_m^{th}$ slightly increases with temperature, in contrast with the behavior of $\lambda_m^{el}$ for the same magnetic field and temperature range; ii) at high magnetic field (5 T and 9 T), $\lambda_m^{th}$ becomes fairly temperature independent. It is also worth mentioning that the decay of $\lambda_m^{th}$ with increasing magnetic field is different at different temperatures, but saturates above ~2 T in all cases except at 2.5 K [see Fig. 3(f)], in agreement with the case at 300 K shown in Ref. [18]. The origin of the differences between the magnon diffusion lengths will be discussed in the following section.

FIG. 3. (a-b) Non-local voltage amplitude for (a) electrically and (b) thermally excited magnons as a function of injector-detector distance and for different magnetic fields. The diffusive and exponential magnon transport regimes, which are indicated with different colors, are identified from the different decay
of the signal with increasing distance. The red lines are fits in the exponential regime to extract the magnon diffusion length at the corresponding magnetic field applied. The dashed region at the bottom of (a) indicates the noise threshold of the measurement setup. (c-d) Temperature dependence of the magnon diffusion length for (c) electrically ($\lambda^e_m$) and (d) thermally ($\lambda^{th}_m$) excited magnons at different magnetic fields. (e-f) Magnetic field dependence of (e) $\lambda^e_m$ and (f) $\lambda^{th}_m$ at different temperatures. All data correspond to sample 1.

**D. Comparison between electrical and thermal magnon diffusion length.**

In the following, we compare the temperature dependence of $\lambda^e_m$ and $\lambda^{th}_m$ for low (0.03 T) and high (9 T) magnetic fields applied (see Fig. 4).

**Low magnetic field regime.** Let us start with the case of a low magnetic field applied (0.03 T). As discussed before, the relatively low signal generated for electrically excited magnons prevented us to measure $\lambda^e_m$ at low temperatures. However, in the temperature regime from $\sim$70 K to $\sim$100 K, it seems that both $\lambda^e_m$ and $\lambda^{th}_m$ converge to $\sim$6 $\mu$m. Increasing the temperature, however, results in a splitting of both characteristic lengths, with $\lambda^{th}_m$ increasing while $\lambda^e_m$ slightly decreasing, reaching $\sim$9.3 $\mu$m and $\sim$4.8 $\mu$m, respectively, at room temperature. This behavior is in stark contrast to previous results reported in 0.2-µm-thick YIG films, where both magnon diffusion lengths coincide [5,18]. However, as in our 2-µm-thick YIG, recent results in thicker YIG films indicate that the magnon diffusion lengths of electrically and thermally excited magnons might be different [3,11], suggesting that the thickness of the YIG layer might have an influence in the magnon diffusion length.

In order to rule out the possibility of non-local thermal effects influencing the signals, which would lead to a misestimation of $\lambda^{th}_m$, we measured a second sample (sample 2) with devices with longer injector-detector distances. As discussed in Appendix C, we can clearly distinguish the exponential regime, from which $\lambda^{th}_m$ can be extracted reliably, from the $1/d^2$-regime, which is dominated by the thermal gradient generated at the GGG/YIG interface underneath the detector [11]. By fitting the data to the entire exponential regime (which ranges up to $\sim$40 $\mu$m), we obtain $\lambda^{th}_m$ values that are in good agreement with the values extracted from sample 1 (see Fig. 5). We thus conclude that both $\lambda^{th}_m$ and $\lambda^e_m$ are properly evaluated for the case of a small magnetic field applied and, more importantly, they are different in the temperature range 100-300 K. The captured trend for $\lambda^e_m(T)$ suggests that it may converge with $\lambda^{th}_m(T)$ at lower temperatures (Fig. 4, solid symbols). However, the relatively small non-local signal measured for electrically excited magnons at low temperatures (note that both the reduction of the temperature, see Fig. 2(a), as well as the thickness of the YIG film contribute to a reduction of the signal [4–6,18]) impede us to evaluate their diffusion length in this regime and, consequently, prevented us to extract solid conclusions about the possible convergence of both magnon diffusion lengths at low temperatures.
The large difference observed between the magnon diffusion length for electrically and thermally excited magnons (which approaches to a factor of two at room temperature) evidences that the magnons generated at the YIG/Pt-injector interface diffuse and relax differently depending on the way they are excited. First reports in thinner films [4,5,18] (0.2 µm, whereas here we study a 2.0 µm-thick YIG), however, suggested that both methods result in the creation and propagation of equivalent magnon populations. From a theoretical perspective, given that it was possible to model the magnon transport experiments by employing a single relaxation parameter, it was believed that the magnon transport is dominated by the diffusion of thermal magnons [4,13]. More recent reports, however, showed hints that the magnon diffusion length of electrically excited magnons may differ from those excited thermally in thick films [3,11], with \( \lambda_{m}^{e} \) values found that are surprisingly similar to the one extracted here (\( \lambda_{m}^{e} \sim 6 \mu m \) at room temperature [3]). The existence of such discrepancy, however, was not discussed.

In order to understand the origin of the discrepancy between \( \lambda_{m}^{e} \) and \( \lambda_{m}^{th} \), we note that studies of the longitudinal spin Seebeck effect in YIG/Pt showed that sub-thermal magnons, i.e., magnons that have energies below \( k_{B}T \), interact more strongly with the electrons in Pt [36]. The critical temperature at which the sub-thermal magnons become noticeable in the experiment was estimated to be \( T_{c} \sim 40 \) K. Conversely, it is known that current-driven torques couple more efficiently to low-frequency magnons [37]. We therefore interpret our results as the direct consequence of the excitation of different magnon populations, i.e., sub-thermal or thermal magnons, depending on whether the generation is produced by current-driven torques or by local thermal gradients (note that the excitation of magnon currents by thermal means do not require that the Pt injector and the YIG film are in direct contact, but to generate a local hot spot [3]). Interestingly, the temperature dependence of the two magnon diffusion lengths indicate that they may converge at low temperatures (Fig. 4), where both electrical and thermal methods should excite similar magnon populations. Our results demonstrate that the magnon diffusion length is frequency-dependent, and evidence that the method and conditions at which the magnons are excited can strongly influence the magnon diffusion length, thus calling for more complex models to accurately describe diffusive magnon currents in magnetic systems. Experiments such as frequency-dependent coherent generation and propagation
of magnon currents could shed some light on these questions. The role of the YIG thickness on the magnon transport for electrically excited magnons is not understood at the moment. However, we speculate that thin YIG films may favor a magnon overpopulation, even for moderate current-driven torques, or that the scattering at the YIG/GGG interface enhances the magnon scattering and thus their thermalization. Both mechanisms would result in a deformation of the magnon population for the electrically excited magnons towards the one generated by thermal means, and hence explaining the similar magnon diffusion length extracted from both methods.

**High magnetic field regime.** We now turn to the case of high magnetic fields (>2 T), a regime in which both magnon diffusion lengths reduce with respect to the low field case (compare, for instance, open and solid symbols in Fig. 4), an effect that is more evident for temperatures above ~100 K. Moreover, in contrast to the case of low magnetic fields, \( \lambda_{m}^{th} \) and \( \lambda_{m}^{el} \) do not coincide at any temperature, with a difference that increases up to a factor of four for temperatures above 100 K. This large difference is due to the strong decay of \( \lambda_{m}^{el} \) with magnetic field [Fig. 3(e)], whereas \( \lambda_{m}^{th} \) tends to saturate [Fig. 3(f)]. This different behavior of the diffusion lengths with magnetic field was already reported by Cornelissen et al. in a 0.2-μm-thick YIG at room temperature and was interpreted as an artifact arising from the temperature gradients present close to the detector [18].

Indeed, the influence of such thermal gradients gives rise to long ranged non-local signals \( (1/d^2\text{--regime}) \), which are expected to dominate at distances longer than 3–5 times the magnon diffusion length [11]. Although we have ruled out this possibility at low fields (Appendix C), the decay of \( \lambda_{m}^{th} \) with increasing the magnetic field [Fig. 3(f)] might lead to a shift of the \( 1/d^2\text{--regime} \) to shorter distances. Whereas at 2 T we can still clearly distinguish the exponential regime from the \( 1/d^2\text{--regime} \), at 5 and 9 T they cannot be distinguished (see Appendix C). These are precisely the magnetic fields at which \( \lambda_{m}^{th} \) tends to saturate [Fig. 3(f)]. Although we cannot unequivocally confirm this, our observations suggests that the apparent saturation of \( \lambda_{m}^{th}(H) \) above 2 T could arise from an overestimation of the magnon diffusion length caused by the fitting of the non-local signal in a region partially influenced by the thermal gradients. Alternatively, the different magnetic-field dependence of \( \lambda_{m}^{el} \) and \( \lambda_{m}^{th} \) could be originated by the different origin of the two type of excited magnons (sub-thermal vs thermal, respectively).

**E. Robustness of the thermal magnon diffusion length with YIG thickness.**

In the following, we show that the temperature dependence of the magnon diffusion length of the thermally excited magnons at low fields is the same regardless of the YIG thickness. In Fig. 5, we present the temperature dependence of \( \lambda_{m}^{th} \) for our 2-μm-thick YIG (blue solid squares for sample 1 and cyan solid circles for sample 2), together with the data of two previous works: a single crystal of YIG (500 μm) grown by Czochralski method [6] (black open triangle), and a thinner YIG with a thickness of 0.2 μm grown by LPE [5] (red open triangle). Interestingly, the magnon diffusion lengths in all four samples have the same temperature dependence and comparable amplitude. This surprisingly good match evidences that the YIG thickness and the growth method are not relevant parameters that determine how far thermally excited magnon currents can flow through YIG, showing the robustness of the extracted values. Considering that these are independent measurements in three different experimental setups, but that in all of them a local thermal gradient is generated for creating the magnon currents, we conclude that
\( \lambda_m^{th} \) is an intrinsic parameter of YIG that is associated to the diffusion of thermal magnons. We should mention here that the temperature dependence of \( \lambda_m^{th} \) for a 2.7-\( \mu \)m-thick YIG sample (a thickness similar to ours) is also studied in Ref. [11]. \( \lambda_m^{th} \) has the same trend with temperature, but with larger values: \( \lambda_m^{th} \) at room temperature is \( \sim 15 \mu \)m and the maximum value at the lowest temperature rises up to \( \sim 40 \mu \)m. We do not find an easy explanation for the difference between our values and the ones reported in Ref. [11], which might need further investigation.

![Graph showing temperature dependence of magnon diffusion lengths](image)

**FIG. 5.** Comparison of the temperature dependence of the magnon diffusion lengths of thermally excited magnons for different YIG thicknesses and growth method: 2 \( \mu \)m (sample 1 and 2, this work), 500 \( \mu \)m [6], and 0.2 \( \mu \)m [5].

**IV. Conclusions**

Our magnon transport experiments performed in 2-\( \mu \)m-thick YIG films reveal clear differences in the diffusion lengths of electrically and thermally excited non-equilibrium magnon currents. The origin of such difference is attributed to the different non-equilibrium magnon distributions excited depending on the driving mechanism, i.e., sub-thermal and thermal magnon distributions for electrically and thermally excited magnons, respectively, suggesting that the properties of diffusive magnons are frequency dependent. The effect is clearly noticeable at the highest temperature explored (300 K), in which the energy difference between the thermal and sub-thermal magnons is maximum — being the magnon diffusion length of the thermally excited ones larger —, and gradually disappears as the temperature decreases. Moreover, the damping of the magnon currents is also magnetic field dependent, being the electrically excited magnons more damped by external magnetic fields than those thermally excited. In the case of large magnetic fields, we cannot rule out an overestimation of the magnon diffusion length for thermally excited magnons, as the non-local thermal gradients occurring in the \( 1/d^2 \)–regime might dominate at lower distances. Finally, we demonstrate that, at low magnetic fields, the same temperature dependence and size of the magnon diffusion length is obtained for thermally excited magnons in YIG samples of different thicknesses and growth conditions, demonstrating the robustness of the measurement method and that this quantity is indeed an intrinsic parameter of YIG.

**Acknowledgments**
Appendix A: Current dependence of the non-local spin Seebeck effect signal at low temperatures.

Figure 5(a) shows the angular-dependent non-local spin Seebeck signal \( V_{NL}^{th} \), normalized to the square of the injected current, for different currents at the lowest temperature measured (\( T = 2.5 \) K). The curves at lower currents do not overlap, evidencing a non-quadric dependence of the non-local voltage \( V_{NL}^{th} \). This anomaly is also observed in Fig. 5(b), which shows that \( V_{NL}^{th} \) does not scale with \( I^2 \) at low currents (\( I \lesssim 50 \) μA). At higher currents, however, \( V_{NL}^{th} \) follows a quadratic dependence with the current, as evidenced by the linear dependence with \( I^2 \) above \( I \sim 70 \) μA [Fig. 5(b)]. This range is the one used for extracting \( \lambda_{mt} \). The current dependence of \( V_{NL}^{th} \) in the low current regime is rather linear [see Fig. 5(c)]. This linear dependence has already been reported in YIG at 3 K [34], but its origin remains unclear. Understanding this deviation from the expected behavior would require further studies that are beyond the scope of this work.
FIG. 5. (a) Angular dependence of the non-local signal $V_{NL}$ taken for a magnetic field of 0.03 T rotating in the plane of the film and for different currents applied. The non-local voltage is normalized to the square of the applied current. Measurement temperature, 2.5 K. (b,c) Amplitude of the non-local voltage as a function of the (b) square of the current and (c) the current. All data correspond to Sample 1.

Appendix B: Comparison of the temperature dependence of the non-local signal for electrically excited magnons and of the spin Hall magnetoresistance.

Figure 6(a) shows the amplitude of the non-local signal measured for electrically excited magnons as a function of temperature and for more injector-detector distances than the ones shown in Fig. 2(a). The temperature dependence of the signal follows the same trend as observed in Fig. 2(a), although the magnetic field applied in these measurements is 1 T. Note that, whereas a signal can still be detected at temperatures below 50 K for
distances up to 4 μm, the signal falls below the noise level at larger distances, preventing us from extracting the magnon diffusion length below 50 K.

Figure 6(b) shows the temperature dependence of the spin Hall magnetoresistance (SMR) measured in different Pt stripes. The SMR is a local magnetoresistance that arises from the interplay between spin accumulation generated in the Pt strip with the magnetic moments of the YIG layer [38,39] and is thus closely related to the electrical excitation of magnons studied here [4,13]. We evaluated the SMR in our devices by measuring the longitudinal resistance $R_L$ of the Pt strips while rotating the magnetic field in the plane of the film. The amplitude of the resistance modulation, $\Delta R_L$, is extracted from fitting the signal obtained to the expected $\sin^2 \alpha$ dependence [38], being the ratio $\Delta R_L / R_L$ the amplitude of the SMR. The temperature dependence of the SMR shows a characteristic maximum around 100 K, following a trend that was previously reported by us [19,40], as well as by other groups [41]. According to the SMR theory [38,42], the amplitude of the SMR is defined as

$$\frac{\Delta \rho_L}{\rho} = \theta_{SH}^2 \frac{\lambda}{t} Re \frac{2 \lambda G_{11} \tanh^2 \frac{t}{\lambda}}{\sigma + 2 \lambda G_{11} \cosh \frac{t}{\lambda}} ,$$

where $\theta_{SH}$, $\lambda$, $t$, and $\sigma$ are the spin Hall angle, spin diffusion length, thickness, and conductivity of the Pt, respectively, and $G_{11} = G_r + i G_i$ is the spin-mixing conductance, which quantifies the spin transport through the interface. Therefore, SMR only depends on the Pt parameters and the spin transmission efficiency of the interface. In the particular case of YIG, $G_r \gg G_i$ [38,43], and thus $G_{11}$ is governed by $G_r$, which is temperature independent [13,44] for the range explored in this experiment [42,45]. This means that the temperature dependence of the SMR is related to the spin Hall efficiency of the excitation and detection at the Pt/YIG interface [4], which would explain the behavior of the non-local signal observed in Figs. 2(a) and 6(a).
FIG. 6. (a) Temperature dependence of the non-local voltage amplitude, normalized to the applied charge current (150 μA), for electrically excited magnons at \( H = 1.0 \) T and for different injector-detector distances. (b) Temperature dependence of the amplitude of the spin Hall magnetoresistance measured in different Pt stripes at \( H = 1.0 \) T. A current of 150 μA was used. All data corresponds to Sample 1.

Appendix C: Distance dependence of the non-local signal for thermally excited magnons.

In order to determine the different regimes of the non-local thermal signals \( V_{NL}^{th} \) in our YIG films, i.e., the exponential and \( 1/d^2 \) regimes, to ensure that the magnon diffusion length is extracted from the data belonging to the exponential regime, we used sample 2 which contains devices with longer injector-detector distances than the devices in sample 1. Figure 7(a) shows the amplitude of the non-local signal for thermally excited magnons at \( H = 0.03 \) T as a function of \( d \) and for different temperatures. Two different regimes are clearly identified: (i) for distances up to \( d \sim 50 \) μm, a first signal decay is identified, which corresponds to the expected exponential decay of the magnon chemical potential with distance [3–5,11,13,18]. The \( \lambda_{m}^{th} \) extracted in sample 2 in this regime matches well with the values obtained in sample 1 [Fig. 4], confirming that the \( \lambda_{m}^{th} \) extracted in both samples indeed corresponds to the magnon diffusion length of thermally excited magnons; (ii) for \( d > 50 \) μm, a second signal decay with an apparent longer characteristic length is identified. In this region, the system enters in the so-called \( 1/d^2 \)–regime, in which the signal is dominated by the temperature gradients at the YIG/GGG interface beneath the Pt detector [11]. This result is indeed expected for our YIG-thickness and \( \lambda_{m}^{th} \) values, in agreement with Ref. [11]. The two regimes can be clearly distinguished for \( H = 0.03 \) T and 2 T [black solid and green open squares in Fig. 7(b)]. However, at \( H = 5 \) T and 9 T [red solid circles and blue solid triangles and green squares in Fig. 7(b), respectively], it is difficult to evaluate the existence of both regimes as no clear change in the slope of the
signal decay with $d$ can be identified, indicating that, at the largest measured distances, both magnon transport and non-local thermal gradients might contribute to the non-local $V_{NL}^{th}$ signal. Note that, with increasing the magnetic field, $\lambda_{th}^{mt}$ decreases and then the emergence of the $1/d^2$ regime would shift to shorter distances. In this case, and only for these large magnetic fields, we could be overestimating $\lambda_{th}^{mt}$. The saturation of $\lambda_{th}^{mt}$ with magnetic field above ~2 T might be indicating that this is the case [Fig. 3 (f)].

![Diagram](image)

**FIG. 7.** Distance dependence of the amplitude of the non-local voltage for thermally excited magnons taken at different temperatures in Sample 2. The signal is normalized to the square applied charge current (150 $\mu$A) and the length of the detector ($L$). The measurement field is $H = 0.03$ T. Two different regimes are identified: the exponential regime, for $d < 50 \, \mu$m, and the $1/d^2$-regime, for $d > 50 \, \mu$m. (b) Distance dependence of the non-local voltage for thermally generated magnons at $T = 100$ K and different magnetic fields. The two regimes are clearly distinguishable for low magnetic fields ($H = 0.03$ T and 2 T). However, at high magnetic fields it is difficult to evaluate the distance at which the threshold between the two regimes occurs.

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