Controlling spins in nanodevices via spin-orbit interaction, magnons and heat

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Chapter 8

Efficient injection and detection of out-of-plane spins via the anomalous spin Hall effect in permalloy nanowires

Abstract

We report a novel mechanism for the electrical injection and detection of out-of-plane spin accumulation via the anomalous spin Hall effect (ASHE), where the direction of the spin accumulation can be controlled by manipulating the magnetization of the ferromagnet. This mechanism is distinct from the spin Hall effect (SHE), where the spin accumulation is created along a fixed direction parallel to an interface. We demonstrate this unique property of the ASHE in nanowires made of permalloy (Py), to inject and detect out-of-plane spin accumulation in a magnetic insulator, yttrium iron garnet (YIG). We show that the efficiency for the injection/detection of out-of-plane spins can be up to 50% of that of in-plane spins. We further report the possibility to detect spin currents parallel to the Py/YIG interface for spins fully oriented in the out-of-plane direction, resulting in a sign reversal of the non-local magnon spin signal. The new mechanisms that we have demonstrated are highly relevant for spin torque devices and applications.

Published as:
K. S. Das, F. K. Dejene, B. J. van Wees and I. J. Vera-Marun
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8.1 Introduction

Electrical injection and detection of spin currents plays an essential role for the technological implementation of spintronics. The conventional way of electrical spin injection is by driving a spin-polarized current from a ferromagnet into a normal metal [1]. This method, however, is limited in the scalability and direction of the injected spin current, which is parallel to the charge current, and has motivated the study of alternative methods based on the spin Hall effect (SHE) present in heavy non-magnetic metals [2, 3]. The SHE generates a spin current perpendicular to a charge current, which is particularly significant for spin torque applications [4–8] and for spin injection into magnetic insulators [9–11].

However, the spin direction of the spin accumulation generated via the SHE is fixed, parallel to the interface, depending only on the direction of the charge current through the heavy non-magnetic metal [Fig. 8.1(a)]. Alternatively, the anomalous Hall effect [12] in ferromagnetic metals can be used as a tunable source of transverse spin current, as has been theoretically predicted [13–15] and recently demonstrated experimentally [16–19]. We call this phenomenon the anomalous spin Hall effect (ASHE), which generates a spin accumulation oriented parallel to the ferromagnet’s magnetization [Fig. 8.1(b) - 8.1(d)]. In principle, the ASHE provides a novel way of electrically injecting and detecting a spin accumulation with out-of-plane components, which can be controlled by manipulating the ferromagnet’s magnetization.

Here, we experimentally demonstrate the versatility of the ASHE for electrically injecting and detecting spin accumulation oriented in arbitrary directions, parallel to the ferromagnet’s magnetization, in a proof-of-concept device geometry. We utilize the ASHE in a nanowire made of a ferromagnetic metal, permalloy (Ni₈₀Fe₂₀, Py), to inject a magnon spin accumulation in a magnetic insulator, yttrium iron garnet (Y₃Fe₅O₁₂, YIG). The injected magnon spins are electrically detected at a second Py nanowire. This non-local geometry, shown in Fig. 8.2(a), and the insulating property of the YIG film ensure that we exclusively address spin-dependent effects, free from magnetoresistance due to the magnetization of the Py nanowire (Mₚ). Moreover, the YIG film serves as a selector of the spin components from the Py injector, since only the spin component parallel to the YIG magnetization (Mᵧ) will result in the generation of magnon spin accumulation in the YIG film [9]. We apply an external magnetic field (B) at different out-of-plane angles for the distinct manipulation of the magnetizations Mₚ and Mᵧ. Therefore, we control both the direction of the injected and detected spin accumulation generated by the ASHE (parallel to Mₚ), and the efficiency of the magnon injection and detection process (via the projection of Mₚ on Mᵧ). Furthermore, we detect a finite non-local signal with a negative sign when both Mₚ and Mᵧ are oriented fully perpendicular to the sample (xy) plane. We attribute this to a second mechanism of generation and detection
Figure 8.1: Schematic illustration of: (a) the spin Hall effect (SHE) in a metal with high spin-orbit coupling, (b-d) the anomalous spin Hall effect (ASHE) in a ferromagnetic metal for three different orientations of the ferromagnet’s magnetization (M) and a fixed charge current (I). The magnitude and the direction of the spin current generated due to the ASHE is given by $M \times I$, with the spin accumulation direction parallel to $M$. Spin accumulation with both in-plane and out-of-plane components is generated at the bottom interface when $M$ tilts out of the plane, as shown in (c). The contribution of the out-of-plane component of the spin accumulation at the bottom interface is given by $\sin \theta \cos \theta$ and reaches a maximum of 50% when $\theta = 45^\circ$, compared to the contribution of the in-plane spin component at the bottom interface when $\theta = 0^\circ$. Spin accumulation exclusively oriented perpendicular to the top/bottom interface is achieved at the edges when $M$ is oriented completely in the out-of-plane direction, as shown in (d). The dashed arrows indicate the directions of the spin current.

of horizontal spin currents, parallel to the Py/YIG interface. The efficiency of this injection/detection mechanism is maximum when the spins are fully oriented in the out-of-plane direction. Besides its possible use for magnon transistor and magnon-based logic operations [20–22], this model system is also highly relevant for spin torque applications [4–8].
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8.2 Experimental details

The devices were patterned using electron beam lithography on a 210 nm thick YIG film, grown on a GGG (Gd$_3$Ga$_5$O$_{12}$) substrate by liquid-phase epitaxy. A scanning electron microscope (SEM) image of a representative device is shown in Fig. 8.2(b). The devices consist of two Py nanowires (left and middle) and one Pt nanowire (right) with thicknesses of 9 nm (Py) and 7 nm (Pt), respectively. The Py and the Pt nanowires were deposited by d.c. sputtering in Ar$^+$ plasma. Electron beam evaporation was used to deposit the Ti/Au leads and bonding pads following the final lithography step (see Supporting Information section 4 for additional details on device fabrication). The middle Py nanowire is used as the spin injector, while the outer Py and Pt nanowires are used as detectors. The width of the middle Py injector is 200 nm and that of the outer Py and Pt detectors is 400 nm. The edge-to-edge distance between the injector and the detectors is 500 nm. The electrical connections are also depicted in Fig. 8.2(b). An alternating current ($I$), with an rms amplitude of 310 $\mu$A and frequency of 5.5 Hz, is sourced through the middle Py injector. The non-local voltages across the left Py detector ($V_{Py}$) and the right Pt detector ($V_{Pt}$) are simultaneously recorded by a phase-sensitive lock-in detection technique. The first harmonic response ($1f$) of the non-local voltage corresponds to the linear-regime electrical spin injection and detection via the (A)SHE and their reciprocal processes. The second harmonic (2$f$) response, driven by Joule heating at the injector and proportional to $I^2$, corresponds to the thermally generated magnons near the injector via the spin Seebeck effect (SSE) [9, 23] which travel to the detector. At the Py detector, a lateral temperature gradient along the $x$-axis also contributes to an electrical signal via the anomalous Nernst effect (ANE) [24, 25]. The non-local voltage [$V^{12f}$] measured across the detectors has been normalized by the injection current ($I$) for the first harmonic response ($R_{NL}^{1f} = V^{1f}/I$) and by $I^2$ for the second harmonic response ($R_{NL}^{2f} = V^{2f}/I^2$). The experiments have been conducted in a low vacuum atmosphere at 293 K.

8.3 Results and Discussion

To explore the injection/detection of out-of-plane spins, we performed magnetic field ($B$) sweeps within the $xz$-plane, at different angles $\phi$ with respect to the $x$-axis [see Fig. 8.2(a)]. The first harmonic responses ($R_{NL}^{1f}$) measured by the Py and the Pt detectors are plotted as a function of $B$ in Figs. 8.2(c) and 8.2(d), respectively. $R_{NL}^{1f}$ comprises of magnon spin injection and detection due to two different mechanisms: (i) SHE (independent of $M_{Py}$) and (ii) ASHE (maximum contribution when $M_{Py}$ is...
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Figure 8.2: (a) Schematic illustration of the experimental geometry. The ASHE and its reciprocal effect in Py are used to inject and detect magnons in the YIG film. An external magnetic field ($B$) is applied in the $xz$-plane, at an angle $\phi$ with respect to the $x$-axis, to manipulate the magnetizations of Py ($M_{Py}$) and YIG ($M_{YIG}$). (b) SEM image of a representative device illustrating the electrical connections. An alternating current ($I$) is sourced through the injector (middle Py nanowire). The corresponding non-local voltages across the left Py detector ($V_{Py}$) and the right Pt detector ($V_{Pt}$) are measured simultaneously. (c-d) The first harmonic response of the non-local resistance ($R_{NL}^{1f}$) is plotted as a function of $B$ applied at different angles ($\phi$), measured by the Py detector (c) and the Pt detector (d). Symbols represent experimental data, while solid black lines are modelled curves following Eq. 8.1 and Eq. 8.2 for the Py and the Pt detectors, respectively.

perpendicular to $I$) [16]. The SHE results in a constant spin accumulation oriented along the $x$-axis at the bottom interface of the injector, which leads to a maximum magnon spin injection when $M_{YIG}$ is also oriented parallel to the $x$-axis. Since the YIG
film has a small in-plane coercivity of less than 1 mT, \( M_{YIG} \) will be oriented along the x-axis at low magnetic fields. This gives rise to a signal of 0.35 mΩ at the Py detector [Fig. 8.2(c)] and 1.30 mΩ at the Pt detector [Fig. 8.2(d)] for \( B \sim 0 \). At such low fields \( M_{Py} \) is oriented along the Py nanowire (y-axis) due to shape anisotropy, thus only the SHE contributes to the magnon injection and detection processes. The ASHE starts to contribute when \( M_{Py} \) has a component oriented perpendicular to \( I \), and becomes maximum when \( M_{Py} \) is parallel to the x-axis [see Fig. 8.1(b)]. Therefore, the maximum non-local signal is attained for \( \phi = 0^\circ \) when \( B > 50 \) mT, corresponding to \( M_{Py} \) oriented along the x-axis [16].

As the angle \( \phi \) is increased, the z-components of \( M_{Py} \) (\( M_{Py}^z \)) and \( M_{YIG} \) (\( M_{YIG}^z \)) increase, while the x-components (\( M_{Py}^x \) and \( M_{YIG}^x \)) decrease. The schematic shown in Fig. 8.1(c) depicts the case when \( M_{Py} \) is oriented at an angle \( \theta \) with respect to the positive x-axis, such that \( 0^\circ < \theta < 90^\circ \). The contribution of the out-of-plane spin component to the spin accumulation at the bottom interface is given by \( \sin \theta \cos \theta \) and reaches a maximum of 50% when \( \theta = 45^\circ \), compared to that of the in-plane spin component (given by \( \cos^2 \theta \)) when \( \theta = 0^\circ \). When \( M_{Py} \) is oriented fully perpendicular to the bottom interface [Fig. 8.1(d)], spin accumulation with only out-of-plane components are created at the left and right edges of the Py nanowire. In this case, the spin injection and detection efficiency through the bottom interface is expected to be zero.

However, when \( B \) is applied almost perpendicular to the plane of the sample (\( \phi = 89^\circ \)) the first harmonic response \( R_{NL}^F \) measured by the Py detector changes sign and becomes negative. This result cannot be explained within the standard framework of (SHE driven) transport dominated by in-plane spins, where a vanishing signal is expected [9–11]. We therefore argue that such a negative signal can only be understood by the injection/detection mechanism of spin currents parallel to the x-axis via the ASHE, the efficiency of which is maximized for spins oriented fully along the z-axis [see Fig. 8.1(d)]. This is consistent with \( R_{NL}^F \) measured by the Pt detector, which is zero, as expected from the lack of the ASHE detection in the Pt nanowire. Furthermore, we have unambiguously established the linearity (see Supporting Information section 7 on the absence of any third harmonic response) and the reciprocity (see Supporting Information section 8 for measurements using a Pt injector and a Py detector) of the non-local signal. Thus, a spin accumulation with an exclusively out-of-plane component can only be injected and detected via the ASHE and, in our sample geometry, results in a distinct negative polarity of the non-local signal.

Further understanding is achieved by studying the second harmonic response measured by the Py and Pt detectors, shown in Figs. 8.3(a) and 8.3(b), respectively. The temperature gradient generated due to Joule heating at the injector drives the
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Figure 8.3: (a) The second harmonic response of the non-local resistance ($R_{NL}^{2h}$) measured by the Py detector has two contributions: the anomalous Nernst effect (ANE) (proportional to $M_{Py}^z$) and the spin Seebeck effect (SSE) (proportional to $M_{YIG}^x$). (b) The $R_{NL}^{2h}$ measured by the Pt detector is only due to the SSE, which decreases as $M_{YIG}^x$ increases. $M_{Py}^z$ (c) and $M_{YIG}^x$ (d) are plotted against $B$ for the different out-of-plane angles ($\phi$). The magnetizations are extracted from the Stoner-Wohlfarth model, by fitting the second harmonic responses (discussed in the Supporting Information).

Spin Seebeck effect (SSE), and the generated magnons are detected by the Pt nanowire via the inverse spin Hall effect (ISHE) and by the Py detector as a combination of the ISHE and the inverse ASHE. In addition to these spin detection processes, at the Py detector the ANE also contributes to $R_{NL}^{2h}$. Starting with the case $\phi = 0^\circ$, when $M_{Py}$ is oriented along the $x$-axis, only the SSE contributes to $R_{NL}^{2h}$ measured...
by the Py detector, with a negligible ANE contribution due to the small temperature gradient along the z-axis within the Py detector. However, when \( \phi \neq 0^\circ \) and the z-component of \( M_{\text{Py}} \) increases, the ANE starts to dominate and is maximized for \( \phi = 90^\circ \), whereas the contribution due to the SSE goes down as the x-component of \( M_{\text{YIG}} \) decreases. We therefore consider \( \text{ANE} \propto M_{\text{Py}}^z \) and \( \text{SSE} \propto M_{\text{YIG}}^x \), and employ the Stoner–Wohlfarth model [26] to extract from \( R_{\text{NL}}^2 \) the magnetization behaviour of the Py nanowire and the YIG film (see Supporting Information section 1). From these second harmonic measurements, we conclude the absence of any significant interfacial exchange interaction, which if present, would lead to effective exchange fields below 1 mT (see Supporting Information section 5), in agreement with our previous experimental results [16]. The extracted \( M_{\text{Py}}^z \) and \( M_{\text{YIG}}^z \) are plotted as a function of \( B \) for different angles \( \phi \) in Figs. 8.3(c) and 8.3(d), respectively. The different mechanisms contributing to the second harmonic response have been summarized in the Supporting Information section 9.

We use the extracted magnetization behaviour of the Py nanowires and the YIG film to model the first harmonic response via the following expressions,

\[
R_{\text{NL}}^{1f}(\text{Py}) = [aM_{\text{YIG}}^x + bM_{\text{Py}}^x(M_{\text{YIG}} \cdot M_{\text{Py}})]^2 - [\eta bM_{\text{Py}}^z(M_{\text{YIG}} \cdot M_{\text{Py}})]^2,
\]

\[
R_{\text{NL}}^{1f}(\text{Pt}) = cM_{\text{YIG}}^x[aM_{\text{YIG}}^x + bM_{\text{Py}}^x(M_{\text{YIG}} \cdot M_{\text{Py}})],
\]

where, \( (M_{\text{YIG}} \cdot M_{\text{Py}}) = (M_{\text{YIG}}^x M_{\text{Py}}^x + M_{\text{YIG}}^y M_{\text{Py}}^y + M_{\text{YIG}}^z M_{\text{Py}}^z) \), with \( M_{\text{YIG}} \) and \( M_{\text{Py}} \) being unitary vectors. The coefficients \( a \), \( b \) and \( c \) can be expressed as \( a \propto \frac{G_{\text{Py}} \theta_{\text{SH}}^\text{Py} \lambda_{\text{Py}}}{t_{\text{Py}} \sigma_{\text{Py}}} \), \( b \propto \frac{G_{\text{Py}} \theta_{\text{SH}}^\text{Py} \lambda_{\text{Py}}}{t_{\text{Py}} \sigma_{\text{Py}}} \) and \( c \propto \frac{G_{\text{Py}} \theta_{\text{SH}}^\text{Py} \lambda_{\text{Py}}}{t_{\text{Py}} \sigma_{\text{Py}}} \) [16]. Here, \( G_{\text{Py}}(\text{Pt}) \), \( \theta_{\text{SH}}(\text{Pt}) \), \( \lambda_{\text{Py}}(\text{Pt}) \), \( t_{\text{Py}}(\text{Pt}) \) and \( \sigma_{\text{Py}}(\text{Pt}) \) represent the effective spin mixing conductance for the Py(Pt)/YIG interface, the spin Hall angle, the spin relaxation length, the thickness and the charge conductivity of the Py (Pt) nanowire, respectively. \( \theta_{\text{SH}}^\text{Py} \) is the anomalous spin Hall angle of Py. For the simulations, we use \( a = 0.58 (\text{m}\Omega)^{1/2} \), \( b = 0.72 (\text{m}\Omega)^{1/2} \) and \( c = 2.37 (\text{m}\Omega)^{1/2} \), which are extracted by fitting the experimental data at \( \phi = 0^\circ \). This fitting procedure leads to an uncertainty below 10% in determining the values of these parameters, which are consistent with the previously reported values [16].

The first part of Eq. 8.1 within the first set of square brackets, accounts for the spin current directed perpendicular to the Py/YIG interface, as depicted in Fig. 8.4(a). The term with the coefficient \( a \) is related to the (constant) spin accumulation along the x-axis due to the SHE in Py, which is independent of \( M_{\text{Py}} \). This term only depends on \( M_{\text{YIG}}^x \) since the generation of magnons is proportional to the projection of \( M_{\text{YIG}} \) on the spin accumulation direction. The term with the coefficient \( b \) is related to the ASHE in Py, which is maximized when \( M_{\text{Py}} \) is parallel to the x-axis. The ASHE
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Figure 8.4: (a) Mechanism for spin current injection and detection along the $-z$ and the $+z$ directions, respectively, resulting in a positive non-local signal ($V_{NL}$). This mechanism has the maximum contribution to $V_{NL}$ for in-plane spins. (b) Mechanism for spin current injection and the detection along the $x$ direction, parallel to the Py/YIG interface, resulting in a negative $V_{NL}$. This mechanism has the maximum contribution to $V_{NL}$ for out-of-plane spins. The individual contribution of the two different mechanisms to the non-local resistance ($R_{NL}$) measured by the Py detector, following Eq. 8.1, has been plotted in (c) for the injection and detection of vertical spin current, and in (d) for the injection and detection of horizontal spin current.

generates a spin accumulation parallel to $M_{Py}$, thus the magnon generation is also proportional to the projection of $M_{Py}$ on $M_{YIG}$. This term includes both the in-plane and the out-of-plane components of the spin accumulation. Since the injection and detection processes are reciprocal, the term within the square brackets is squared.

The second part of Eq. 8.1 within the second set of square brackets and preceded
by a negative sign, accounts for the spin current parallel to the Py/YIG interface, as depicted in Fig. 8.4(b). The contribution of this part to the magnon injection and detection processes is maximum for out-of-plane spins. It is clear from the symmetry of the ASHE and our measurement geometry that the detection of such in-plane spin currents, with spins oriented in the out-of-plane direction, will result in a negative non-local signal measured by the Py detector [Figs. 8.4(a) and 8.4(b)]. Moreover, the parameter $\eta$ tells us the efficiency of detecting spin currents parallel to the interface for out-of-plane spins as compared to that of detecting spin currents perpendicular to the interface for in-plane spins. By fitting the experimental data, we obtain $\eta = 61\%$.

Note that the detection of the spin current parallel to the interface is achieved exclusively via the ASHE. This is evident in the lack of a negative signal while using the Pt nanowire as a detector, where the only detection mechanism is via the ISHE. Thus the Pt nanowire is only sensitive to the spin current perpendicular to the Pt/YIG interface for in-plane spins. Eq. 8.2 describes the spin injection by the Py injector (following Eq. 8.1) and the detection via the ISHE in the Pt nanowire.

The simulated curves, following Eq. 8.1 and Eq. 8.2, are shown as solid black lines in Figs. 8.2(c) and 8.2(d), respectively. This modelling for all tilt angles ($\phi$) employs the same values for the parameters $a$, $b$ and $c$ as those extracted from the in-plane measurements at $\phi = 0^\circ$. The satisfactory agreement with the experimental data, both in terms of magnitude and lineshape, demonstrates that our model captures the dominant physics of the out-of-plane spin injection and detection processes. To achieve further insight, we separate the modelled contributions of the spin current perpendicular to the interface and the spin current parallel to the interface to the non-local signal at the Py detector, following Eq. 8.1. The results, shown in Figs. 8.4(c) and 8.4(d), present in an explicit manner the contribution of the two different mechanisms of detecting the spin current oriented along the $z$-axis and that along the $x$-axis, respectively, with increasing $\phi$.

Note that, although we understand the different symmetries of the injection/detection mechanisms depicted in Figs. 8.4(a) and 8.4(b), we do not fully understand why these mechanisms have comparable efficiencies, given the specific cross sections of the nanowires. Although at $\phi = 89^\circ$, an equal and opposite out-of-plane spin accumulation is generated at the two lateral edges of the Py injector [Fig. 8.1(d)], we can still measure a finite signal with the Py detector. This is because the contribution from the closest edges of the injector and the detector is expected to dominate the non-local signal in this case (see Supporting Information section 10). The minor disagreement between model and experiment, observed at intermediate values of $B$, can be attributed either to the extraction method of the magnetization behaviour of the Py nanowires and the YIG film, shown in Figs. 8.3(c) and 8.3(d), or could hint to a subtle effect not present in our description. To explore the latter, we have considered a second set of fitting curves with a non-constant $b$ parameter, motivated by
recent studies on spin rotation symmetry and dephasing \cite{27}. The apparent variation of the spin injection and detection processes due to a tilted $M_{Py}$ is of only up to $\sim 20\%$ (see Supporting Information section 2). Note that another possible mechanism for the injection of out-of-plane spins is the anisotropic magnetoresistance (the planar Hall effect) \cite{13}. However, the expected contribution of the planar Hall effect is inconsistent with our experimental observations and it does not affect our quantitative analysis of the ASHE microscopic parameters nor our main conclusions (see Supporting Information section 6). Finally, control experiments and modelling with a different architecture using a Pt injector and a Pt detector have been performed, confirming the absence of injection and detection of out-of-plane spins via the SHE alone (see Supporting Information section 3).

8.4 Conclusions

The present demonstration of electrical injection and detection of spin accumulation in arbitrary directions is highly desirable in spintronics. We envision that the use of out-of-plane spins within transverse spin currents, in a common ferromagnetic metal like permalloy, has the potential to impact spintronic-based technologies like spin-transfer-torque memories \cite{4-8} and logic devices \cite{20-22}. Further remains both on the fundamental understanding, and on the possible implications for previous SHE studies, where the control of spin transport efficiency and directionality enabled by the ASHE \cite{16-19} has not been hitherto considered.
8.5 Supporting information

8.5.1 Determination of the Py and the YIG magnetization orientations

In this section, we will discuss the procedure for determining the orientation of $M_{\text{Py}}$ and $M_{\text{YIG}}$.

A magnetic field $B$ is applied at an angle $\phi$ with respect to the $x$-axis, as shown in Fig. 8.5(a). For every field-sweep curve, we sweep the magnitude of $B$ in both positive and negative directions. The applied $B$ has both in-plane and out-of-plane components with respect to the plane of the YIG film. The sample is aligned in such a way that $B$ is in the $xz$-plane. Therefore, we can simply express $B$ as

$$B = (B_x, 0, B_z) = (B \cos \phi, 0, B \sin \phi)$$

where $\phi$ is the angle between $B$ and x-axis. The orientation of $M_{\text{Py}}$ and $M_{\text{YIG}}$ does not only depend on $B$ but also the saturation magnetization ($M_{s,\text{Py}}$ and $M_{s,\text{YIG}}$) and the shape of the magnets.

Firstly, we write the magnetization of the Py as

$$M_{\text{Py}} = (M_{x,\text{Py}}, M_{y,\text{Py}}, M_{z,\text{Py}})$$

and we define the angle between $M_{\text{Py}}$ and three coordinate axes, $\theta_i$, as

$$\cos \theta_i = \frac{M_{i,\text{Py}}}{M_{s,\text{Py}}}$$

where $i = x, y, z$.

In order to find out $M_{\text{Py}}$ under a given $B$, we can write down the magnetism-related energy density $\varepsilon_m$ for Py

$$\varepsilon_m^{\text{Py}} = E_{\text{Py}}^{\text{Zeeman}} + E_{\text{Py}}^{\text{ani}}$$

where the first term is the Zeeman energy term

$$E_{\text{Py}}^{\text{Zeeman}} = -M_{\text{Py}} \cdot B,$$

and the second term is the anisotropy term

$$E_{\text{Py}}^{\text{ani}} = \sum_{i=x,y,z} K_{i,\text{Py}} \sin^2 \theta_i,$$
where $K_{ij}^p$ is the anisotropy constant of Py along three axes. Due to the shape of Py bar, $M_{Py}$ mostly like to align in the plane of the film and along the bar, i.e. $y$-axis. This translates to a relation of $|K_{Py}^z| > |K_{Py}^x| > |K_{Py}^y|$. To determine the orientation of $M_{Py}$, we can find out the energy minimum by $\partial \varepsilon^m / \partial \theta_i = 0$ and $\partial^2 \varepsilon^m / \partial^2 \theta_i > 0$. When $\varepsilon^m$ reaches its minimum, we obtain

$$\cos \theta_x = \frac{M_{Py} B^x}{2 (K_{Py}^x - K_{Py}^y)}, \quad (8.9)$$

$$\cos \theta_z = \frac{M_{Py} B^z}{2 (K_{Py}^z - K_{Py}^y)}, \quad (8.10)$$

$$\cos^2 \theta_y = 1 - \cos^2 \theta_x - \cos^2 \theta_z, \quad (8.11)$$

which tells us the orientation of $M_{Py}$. Eqs. 8.9, 8.10 and 8.11 hold with increasing the field $B$ until it reaches the critical magnetic field $B_c$, where $\cos^2 \theta_y = 0$. For $B > B_c$, the magnetization of Py lies in the $xz$-plane, namely $M_{Py}^z = 0$. Larger tilting angle $\phi$ corresponds to larger $B_c$. In the regime where $B > B_c$, the magnetization of Py becomes $M_{Py} = (M_{Py}^x, 0, M_{Py}^z)$ and $\cos \theta_y = 0$. Doing the same procedure of finding the minimum of $\varepsilon^m$ for Py, we can obtain the relation of $\theta_x$ as

$$M_{Py}^x B^x \sin \theta_x - M_{Py}^z B^z \cos \theta_x = 2 (K_{Py}^z - K_{Py}^x) \sin \theta_x \cos \theta_x, \quad (8.12)$$

from which we can model the magnetization behaviour of Py in the large field regime ($B > B_c$). Combined with the solution of Eqs. 8.9, 8.10 and 8.11 for $B < B_c$, we get the behaviour of $M_{Py}$ in the full field range. Here, we give two examples of the modelled $M_{Py}$ for $\phi = 27^\circ, 67^\circ$ as shown in Fig. 8.5(b).

Secondly, the orientation of $M_{YIG}$ is also related to $B$, the saturation magnetization ($M_{YIG}^s$) and the shape of the magnet, i.e. the 210-nm-thick YIG thin film in our case. We define the angle between $M_{YIG}$ and three coordinate axes, $\gamma_i$, as

$$\cos \gamma_i = \frac{M_i^{YIG}}{M_{YIG}^s}, \quad (8.13)$$

where $i = x, y, z$. Since the YIG thin film is a very soft magnet with significant in-plane shape anisotropy, i.e. the in-plane coercive field is $\sim 0.6$ mT and the out-of-plane coercive field is $\sim 200$ mT. We assume it has an isotropic easy plane and an out-of-plane hard axis. We also assume that $M_{YIG}$ lies in the same plane as $B$, i.e. $xz$-plane. Therefore, we can write down the $M_{YIG}$ as

$$M_{YIG} = (M_{YIG}^x, 0, M_{YIG}^z), \quad (8.14)$$
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Figure 8.5: (a) Schematic illustration of the measured device in a $xyz$-coordinate system. The YIG film lies in the $xy$-plane. The Py nanowires are aligned along the $y$-axis. An external magnetic field $B$ is applied in the $xz$-plane at an angle of $\phi$ with respect to the $x$-axis. Modelled results for the normalized magnetization components along $x$, $y$- and $z$-axes as a function of magnetic field $B$ for (b) Py ($M^x_{Py}$, $M^y_{Py}$ and $M^z_{Py}$) and (c) YIG ($M^x_{YIG}$, $M^y_{YIG}$ and $M^z_{YIG}$). Here, we show the examples under the condition of $\phi = 27^\circ$ (solid lines), $67^\circ$ (dashed lines). For Py, we use the following parameters: $M^x_{Py} = 5 \times 10^5$ [A/m], $K^z_{Py} = -160$ [kJ/m$^3$], $K^y_{Py} \approx 0$ [kJ/m$^3$] and $K^x_{Py} = -10$ [kJ/m$^3$]. For YIG, we use: $M^x_{YIG} = 2.1 \times 10^5$ [A/m], $K^z_{YIG} = -17$ [kJ/m$^3$] and $K^x_{YIG} = K^y_{YIG} = -1$ [kJ/m$^3$].

which gives rise to the similar situation for the Py magnetization when $B > B_c$. In order to find out the orientation of the magnetization under an external magnetic field $B$, we can write down the magnetism-related energy density $\varepsilon^m_{YIG}$ for YIG. Doing the minimizing procedure for $\varepsilon^m_{YIG}$, we obtain the formula with the same form as Eq. 8.12 for YIG as

$$M^x_{YIG} B^x \sin \gamma_x - M^x_{YIG} B^z \cos \gamma_x = 2 (K^z_{YIG} - K^x_{YIG}) \sin \gamma_x \cos \gamma_x,$$

(8.15)

based on which we model the magnetization behaviour of YIG. In Fig. 8.5 (c), we give two examples of the modelled $M_{YIG}$ for $\phi = 27^\circ, 67^\circ$.

We compare the modelled $M_{Py}$ and $M_{YIG}$ with the measured second harmonic non-local resistance detected by the Py and the Pt detectors, as shown in Fig. 8.6. Note that, we have not considered any interfacial exchange interaction between the Py nanowires and the YIG thin film in modelling the magnetization behaviours. The excellent agreement between the experimental data and the modelled magnetization curves with values of saturation magnetization close to that reported in literature, confirms the absence of any significant interfacial exchange interaction.

Because of the very small in-plane coercive field of our YIG film ($< 1$ mT), any component of the external magnetic field ($B$) along the $x$-axis, will rapidly switch
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Figure 8.6: Normalized second harmonic non-local resistance as a function of the magnetic field strength $B$ with different tilting angles $\phi$ for (a) the Py and (b) the Pt detector. In (a), we have subtracted the spin Seebeck contribution from the measured signals and we attribute the field-dependent response shown here to only the anomalous Nernst effect of the Py detector, which scales with $M_{\text{Py}}^z$. In (b), where the detector is a Pt nanowire, the field-dependent behaviour is only due to the spin Seebeck effect of YIG, which is proportional to the $M_{\text{YIG}}^x$. The symbols represent the measured second harmonic data, while the dashed black lines represent the modelled results based on the magnetization behaviour of the Py nanowire and the YIG film, as shown in Fig. 8.5. The dotted black line in (b) represents the modelling consideration at $\phi = 89^\circ$, corresponding to $M_{\text{YIG}}$ oriented along the $y$-axis for small values of $B$.

$M_{\text{YIG}}$ along the $x$-axis. Since there is always a finite component of $B$ along the $x$-axis, except at $\phi = 89^\circ$, $M_{\text{YIG}}$ is aligned with the $x$-axis at small magnitudes of $B$. This results in the finite $R_{\text{NL}}^\text{f} \approx 0.35 \text{ m}\Omega$ measured by the Py detector and $R_{\text{NL}}^\text{f} \approx 1.30 \text{ m}\Omega$ measured by the Pt detector due to the SHE in the Py injector, as described in the main text. However, at $\phi = 89^\circ$, there is hardly any component of $B$ along the $x$-axis and therefore, no preferential direction of $M_{\text{YIG}}$ induced by $B$. Since the $R_{\text{NL}}^\text{f}$ signal in this case is 0, it implies that $M_{\text{YIG}}$ is oriented along the $y$-axis. Therefore, this condition was considered in the modelling for $\phi = 89^\circ$, as is depicted by the dotted black line in Fig. 8.6(b).

8.5.2 Modelling the first harmonic non-local resistance with an angle-dependent $b$-parameter

As discussed in the main text, we obtain a satisfactory agreement between our modelled results (following Eqs. 1 and 2 of the main text) and the experimental data,
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Figure 8.7: The first harmonic response of the non-local resistance \( R_{1f}^{NL} \) is plotted as a function of \( B \) applied at different angles \( (\phi) \) in the \( xz \)-plane, measured by the Py detector (a) and the Pt detector (b). The symbols represent the experimental data, while the solid black lines represent the modelled curves considering a dependence of the parameter \( b \) on \( \phi \), as shown in (c).

Successfully capturing the physics behind the injection and detection of spin accumulation with out-of-plane components. The modelled results in the main text consider a fixed \( b \)-parameter, obtained by fitting the in-plane magnetic field sweep data \( (\phi = 0^\circ) \). Here, we present another set of modelling results by considering a dependence of the \( b \)-parameter on \( \phi \). The modelled curves, along with the experimental data, are shown in Figs. 8.7(a) and 8.7(b) for the Py detector and the Pt detector, respectively. We obtain an excellent agreement between the model and the measured data at all magnetic field regimes, both for the Py and the Pt detectors. Here, we have used \( b \) as a fitting parameter for obtaining the modelled results. Interestingly, we observe a systematic decrease in \( b \) from 0.72 \( (m\Omega)^{1/2} \) for \( \phi = 0^\circ \) to 0.54 \( (m\Omega)^{1/2} \) for \( \phi = 77^\circ \). However, for \( \phi = 89^\circ \), the value of \( b \) again increases to 0.72 \( (m\Omega)^{1/2} \). At this point we are unsure about the exact physical origin of this behaviour and further study needs to be performed to pinpoint the actual reason. However, this does not contradict our observations and the model presented in the main text, which accurately reproduces the lineshape and the magnitude of the experimentally obtained results in the low and high magnetic field regimes.

8.5.3 Control device with Pt injector and Pt detector

As a control experiment, we fabricated a device with a Pt injector and a Pt detector on the same chip and with the same edge-to-edge separation of 500 nm. Magnetic field sweep measurements were carried out at different tilt angles \( (\phi) \) in the \( xz \)-plane, as
described in the main text. The first \( R_{NL}^{1f} \) and the second \( R_{NL}^{2f} \) harmonic responses of the non-local signal, measured by the Pt detector, are shown in Figs. 8.8(a) and 8.8(b), respectively. Fig. 8.8(b) shows that the magnetization behaviour of the YIG film for this control Pt-Pt device is same as that of the Py devices. More importantly, Fig. 8.8(a) shows the absence of the modulation of the non-local signal via the ASHE, as opposed to the Py-Py and the Py-Pt devices (discussed in the main text) and the sign reversal at \( \phi = 89^\circ \) corresponding to the injection and detection of spins oriented fully perpendicular to the Pt/YIG interface. Using the extracted magnetization behaviour of the YIG thin film (as described in section 1), we can model the first and the second harmonic responses of this control Pt-Pt device with the following expressions,

\[
R_{NL}^{1f}(Pt) = [cM_{x}^{yIG}]^2, \quad (8.16)
\]

\[
R_{NL}^{2f}(Pt) = 22.7M_{x}^{yIG}, \quad (8.17)
\]

where, \( c = 2.32 (\text{m} \Omega)^{1/2} \) (consistent with the value of \( c \) used for the Py injector - Pt detector device in the main text) and the value 22.7 is the magnitude of \( R_{NL}^{2f}(Pt) \) at \( \phi = 0^\circ \). Given the possible uncertainties in extracting the magnetization behaviour of the YIG thin film, we find this agreement between the modelled curves and the experimental data excellent. Thus, this control experiment demonstrates that the out-of-plane spin injection and detection achieved via the ASHE, is absent in the pure SHE case.

### 8.5.4 Device fabrication details

The devices used in this study consist of a 210 nm thick single-crystal (111) \( Y_3\text{Fe}_5\text{O}_{12} \) (YIG) film grown on top of a 500 \( \mu \text{m} \) thick \( \text{Gd}_3\text{Ga}_5\text{O}_{12} \) (GGG) substrate by liquid phase epitaxy, commercially obtained from Matesy GmbH. The Gilbert damping parameter of the YIG thin film was determined to be \( \alpha \approx 1.4 \times 10^{-4} \) from FMR linewidth measurement data provided by Matesy GmbH. Before proceeding with the e-beam lithography (EBL) steps for defining the device pattern, the YIG thin film was subjected to ultrasonication in warm acetone for 1 minute, followed by rinsing in IPA, ethanol and DI water. The devices were prepared in four EBL steps, each followed by e-beam deposition or sputter deposition and resist lift-off steps. In the first EBL step, the Ti/Au markers were defined. In the second and the third EBL steps, the Py and the Pt nanowires were patterned, respectively. In the final EBL step, Ti/Au leads and bonding pads were defined, which are 5 nm/80 nm thick and deposited by e-beam evaporation. The Py and the Pt nanowires were deposited by d.c. sputtering in an \( \text{Ar}^+ \) plasma at an argon pressure of \( (3 - 4) \times 10^{-3} \) mbar. No additional YIG cleaning process was employed before sputtering the nanowires. It
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Figure 8.8: (a) The first ($R^{nl}_1$) and (b) the second ($R^{nl}_2$) harmonic responses of the non-local signal, plotted as a function of $B$ applied at different angles ($\phi$) in the $xz$-plane, for a control device with a Pt injector and a Pt detector. The symbols represent the experimental data, while the solid black lines represent the modelled curves following Eqs. 8.16 and 8.17.

Figure 8.9: An optical image of the device used in the measurements described in the main text. The scale-bar shown in the image corresponds to a length of 20 $\mu$m.

was shown in a previous work from our research group that the sputtering process in itself can result in a cleaner metal/YIG interface as compared to metal deposition by e-beam evaporation [28]. The magnitude of the spin Hall magnetoresistance (SMR) signal for similarly prepared Pt/YIG devices on the same YIG thin film was measured to be $\Delta \rho/\rho = (2.60 \pm 0.09) \times 10^{-4}$, expressed as the relative change in the resistivity of the Pt nanowire [29]. This corresponds to a spin-mixing conductance of
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Figure 8.10: (a) Schematic illustration of an effective exchange field ($B_{ex}$) acting on the YIG thin film due to the Py nanowire, causing $M_{YIG}$ to be aligned at a different angle ($\alpha$) compared to the angle ($\theta$) of the applied external magnetic field $B$. (b) Effect of the exchange field on the lineshape of the non-local angular dependence measurements for an applied external field of $|B| = 10 \text{ mT}$. The solid lines are the modelled lineshapes for different magnitudes and signs of $B_{ex}$. The normalized experimental data is shown as the black symbols, which closely follows the modelled lineshape with $|B_{ex}| = 0 - 1 \text{ mT}$.

$1.60 \pm 0.06 \times 10^{14} \text{ S/m}^2$ for the Pt/YIG interface. Note that the devices used in this study are from a different batch compared to the ones used in our previous paper [16]. An optical image of the measured device is shown in Fig. 8.9.

8.5.5 Interfacial exchange interaction between the Py nanowires and the YIG thin film

An interfacial exchange interaction between $M_{Py}$ and $M_{YIG}$ could, in principle, lead to the pinning of the magnetizations or possibly the formation of magnetic domains in the regime of strong coupling between $M_{Py}$ and $M_{YIG}$. Since there is very little known a priori on the nature and the sign of the exchange interaction between Py and YIG, and in the absence of any micromagnetic or theoretical studies, we have looked into it empirically via the various experimental checks described in our previous paper [16]. Through these checks, we concluded that any interfacial exchange interaction, if present, is weak and does not affect our measurements and their interpretation.

Here, we have performed additional simulations to understand the effect of an exchange interaction on the lineshapes of the angular dependence measurements (in the $xy$-plane) [16]. We have modelled the exchange interaction due to the Py
nanowire in the form of an effective magnetic field, $B_{\text{ex}}$, aligned parallel or antiparallel to $M_{\text{Py}}$ acting on the YIG thin film, as depicted in Fig. 8.10(a). An external magnetic field, $|B| = 10 \text{ mT}$, is applied at an angle $\theta$ with respect to the $y$-axis (the easy axis of the Py nanowire). Since $B$ is much smaller than the saturation field of the Py nanowire, $M_{\text{Py}}$ and consequently, $B_{\text{ex}}$ is always oriented along the $y$-axis. The total magnetic field acting on the YIG thin film can be expressed as,

$$B_{\text{tot}} = B + B_{\text{ex}} = \left( B \sin \theta, B \cos \theta + B_{\text{ex}} \right),$$

(8.18)

where, $B = (B \sin \theta, B \cos \theta)$ and $B_{\text{ex}} = (0, B_{\text{ex}})$. Following Eqs. 8.6 and 8.7 and considering an isotropic easy ($xy$) plane for $M_{\text{YIG}}$, the magnetism-related energy density for the YIG thin film can be expressed as,

$$\varepsilon_{\text{YIG}}^{m} = -M_{\text{YIG}} \sin \alpha \sin \theta - M_{\text{YIG}} \cos \alpha (B \cos \theta + B_{\text{ex}}).$$

(8.19)

Following the minimization procedure for $\varepsilon_{\text{YIG}}^{m}$, we find,

$$\alpha = \tan^{-1} \left( \frac{B \sin \theta}{B \cos \theta + B_{\text{ex}}} \right).$$

(8.20)

Using Eq. 8.20 and Eq. 2 of Ref [16] we can model the lineshapes of the angular dependence measurements for different magnitudes and signs of $B_{\text{ex}}$, as shown by the solid lines in Fig. 8.10(b). It is evident from the modelled curves that an interfacial exchange interaction would clearly affect the lineshape in the angular dependence measurements. However, in our experiments, we do not see this type of distortion in the lineshape. To explicitly show this, we have plotted the normalized experimental data for a device with a Py injector and a Py detector, in the same graph (shown as the black symbols). This strongly suggests that the interfacial exchange interaction is very weak (smaller than an effective field of 1 mT), and does not affect our experimental observations and the conclusions in the angle-dependent analysis about the relative strength of the ordinary spin Hall effect versus the anomalous spin Hall effect [16]. Moreover, for the injection and detection of the out-of-plane spins, we are only interested in the high magnetic field regimes. The magnitudes of the magnetic field used in this study and the out-of-plane saturation fields of the Py nanowires and the YIG thin film being much larger than that for the in-plane measurements [16], any effect of an interfacial exchange interaction will be even smaller in the experiments presented in this paper.
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8.5.6 Spin current injection via the anisotropic magnetoresistance/the planar Hall effect of the Py nanowires

A different mechanism for the injection of out-of-plane spins is the anisotropic magnetoresistance (AMR)/the planar Hall effect (PHE) \cite{Ref13}. This effect, however, is not relevant when $M_{Py}$ is either fully collinear or fully orthogonal to the direction of the charge current $I$ (the y-axis), following Eq. 2 in Ref. \cite{Ref13}. In our experimental geometry, we apply the magnetic field in the $xz$-plane. According to our magnetization extraction simulations, the $y$-component of $M_{Py}$ becomes zero already for fields up to 200 mT. For the AMR/PHE to create spin currents directed towards the interface, $M_{Py}$ should also have a component along the $z$-axis. Therefore, the effect due to this mechanism is maximized when $M_{Py}$ makes an angle of $45^\circ$ with the $y$-axis in the $yz$-plane.

Our quantitative analysis on the injection and detection of out-of-plane spins via the ASHE is based on the saturated regimes at high magnetic fields, where the $y$-component of $M_{Py}$ is zero. Most importantly, for the out-of-plane case ($\phi \approx 90^\circ$), when $M_{Py}$ saturates along the $z$-axis, the AMR/PHE has zero contribution and cannot explain the finite and negative response observed. Furthermore, the quantitative analysis for the in-plane spins, as per our previous work \cite{Ref16}, is based on fully in-plane applied magnetic fields where $M_{Py}$ has no component along the $z$-axis. Therefore, the AMR/PHE neither affects the main interpretation of our experiments nor our quantitative analysis of the ASHE contribution to the spin injection and detection.

Figure 8.11: Spin current components generated by the anisotropic magnetoresistance/the planar Hall effect of the Py nanowires, as a function of $B$ applied at different angles ($\phi$) in the $xz$-plane: (a) $Q_{zz}$, (b) $Q_{zx} = Q_{xz}$, and (c) $Q_{xx}$. Each component of the form $Q_{ij}$ corresponds to spins polarized along the $i$-axis, present in a spin current directed along the $j$-axis.
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We acknowledge that the AMR/PHE can play a role when $M_{Py}$ has a (partial) finite $y$-component. This might contribute to the small disagreement on the magnitude of the response for intermediate fields and angles, and is indeed interesting for studying the evolution of the lineshapes with the strength of the magnetic field. To explore this idea, we explicitly calculate the spin current components due to the AMR/PHE following Eq. 2 in Ref.13,

$$Q_{ij} = -\frac{\hbar}{2e} \eta \sigma_{AMR} m_i m_j m_k E_k,$$

where, each component of the form $Q_{ij}$ corresponds to spins polarized along the $i$-axis, present in a spin current directed along the $j$-axis, $m_i$ is the component of the magnetization along the $i$-axis and $E_k$ represents the applied electric field driving the charge current $I$ ($k = y$ in our experimental geometry). Therefore, the spin current components relevant to our experimental geometry are $Q_{zz}$, $Q_{xz}$, and $Q_{xx}$. Using Eq. (8.21) and our modelled magnetization behaviour of the Py nanowire, we have calculated these spin current components and plotted them in Fig. 8.11. From this figure, it is clear that any significant contribution from the AMR/PHE is only expected for the low field regime below 200 mT and will result in lineshapes inconsistent with our observed response. Therefore, we are forced to conclude that our results do not contain any dominant contribution due to the AMR/PHE. We believe further experiments could be devised to look into detail at this low field regime and for quantifying this potential mechanism for spin injection.

8.5.7 Measurement of the third harmonic response of the non-local signal

Higher order effects can also contribute to the first harmonic response of the non-local signal. In order to explicitly rule out any contribution from non-linear effects, we have measured the third harmonic response of the non-local signal for another Py-Py device. In this device, the edge-to-edge separation between the Py injector and the Py detector is 300 nm. In Fig. 8.12, we have plotted both the first (1f) and the third (3f) harmonic responses of the non-local voltage. An injection current with an rms amplitude of 350 $\mu$A is applied through the Py injector. The 1f and the 3f signals are simultaneously measured using two lock-in amplifiers as a function of the angle $\phi$ at which a constant magnetic field $|B| = 1$ T was applied with respect to the $x$-axis in the $xz$-plane. The 3f signal is zero within our measurement accuracy, while the magnitude and the lineshape of the 1f signal is consistent with the magnetic field sweep measurements presented in the main text. This clearly suggests the absence of any non-linear effect in the first harmonic signal.
8.5.8 Reciprocity check in a control device with a Pt injector and a Py detector

We have carried out non-local measurements in a control device in two configurations: 1) Py injector - Pt detector, and 2) Pt injector - Py detector, for establishing the reciprocity of the injection-detection mechanisms. An injection current with an rms amplitude of 350 µA is used and the magnetic field is swept along the x-axis, perpendicular to the length of the nanowires (φ = 0°), in the measurements shown in Figs. 8.13(a) and (b). In Fig. 8.13(a), the non-local resistance is measured across the Pt nanowire (detector) when the Py nanowire is used as the injector. The measurement is repeated after interchanging the current and the voltage contacts and reversing the direction of the magnetic field, such that the Pt nanowire now acts as the injector electrode. The non-local resistance measured across the Py detector in this configuration is shown in Fig. 8.13(b). We have also performed angular dependence measurements by rotating the sample in the xz-plane under a constant magnetic field of 2 T, in both the configurations 1 and 2, as shown in Figs. 8.13(c) and (d), respectively. These measurements clearly demonstrate the reciprocal nature of the SHE (ASHE) and the ISHE (inverse ASHE) and confirm the reciprocity theorem for four-terminal measurements. Moreover, these measurements also confirm the
Figure 8.13: Non-local measurements with magnetic field sweep along the x-axis ($\phi = 0^\circ$) for a control device with a Py injector and a Pt detector (a), and for the same device with a Pt injector and a Py detector (b). The black and the red arrows indicate the trace and the retrace directions of the magnetic field sweep. Angular dependence measurements performed by rotating the sample in the $xz$-plane under a constant magnetic field of 2 T are shown for the Py injector - Pt detector configuration (c) and for the Pt injector - Py detector configuration (d).

reproducible control of the various magnetizations in our devices.

8.5.9 Different mechanisms contributing to the second harmonic response of the non-local signal

The second harmonic (2f) signal is related to the Joule heating at the injector, which scales with $I^2$ and thus, shows up in the second harmonic response of the lock-in detection. The 2f signal does not depend on the electrical injection of spins via the SHE
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<table>
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<th>Source of the 2f signal</th>
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<td>Joule heating at the injector</td>
<td>ISHE (proportional to $M_{YIG}$)</td>
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<tr>
<td></td>
<td>ISHE+IASHE (proportional to $M_{YIG}$)</td>
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<td></td>
<td>ANE (proportional to $M_{Py}^z$)</td>
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Table 8.1: A summary of the different mechanisms contributing to the second harmonic (2f) response of the non-local signal

or the ASHE in the injector, both of which scales linearly with the current. The Joule heating at the injector leads to the generation of magnons in the YIG via the spin Seebeck effect (SSE) \cite{9, 29}. These magnons diffuse towards the detectors and are converted into an electrical signal via the ISHE in the Pt detector and via the combination of ISHE and the inverse ASHE (IASHE) in the Py detector. In addition to the detection of spins via the ISHE and the IASHE, the anomalous Nernst effect (ANE) also contributes to the transverse charge voltage in the Py detector due to a thermal gradient along the x-axis at the detector. Since the ISHE detection of the magnons generated via the SSE is only proportional to $M_{YIG}^x$ and the ANE is only proportional to $M_{Py}^z$, we utilize the 2f response measured by the Pt detector for studying the magnetization orientation of the YIG thin film, whereas, the ANE contribution to the 2f response measured by the Py detector is utilized for studying the magnetization orientation of the Py nanowires, as described in Sec. 1 of this supporting information. We have clearly separated the contributions due to the ANE and the SSE in the Py detector, as shown in Fig. 3(a) of the main text. The different mechanisms contributing to the 2f signal has been summarized in Table 8.1.

Moreover, at $\phi = 0^\circ$, when the ANE is negligible at the Py detector, we can clearly separate the ISHE and the IASHE detection of the magnons generated via the SSE, as shown in Fig. 8.14 and also described in Ref. 16. The sharp switch at $B \approx 0$, corresponding to the switching of $M_{YIG}$, is followed by the gradual in-plane hard axis saturation of $M_{Py}$. From Fig. 8.14, we can calculate the ratio $(\text{ISHE+IASHE})/\text{ISHE} \approx (a + b)/a \approx 2.35$, where the parameters $a$ and $b$ are related to the charge-to-spin conversion factors in the Py via the SHE and the ASHE, respectively, as described in the main text. We can now compare this ratio with the values of the parameters $a$ and $b$ extracted by fitting the first harmonic (1f) data with our model. In the main text, we have extracted $a = 0.58 \ (\text{m}\Omega)^{1/2}$ and $b = 0.72 \ (\text{m}\Omega)^{1/2}$, which gives us $(a + b)/a \approx 2.24$. This is in excellent agreement with the ratio calculated from the 2f
data, confirming that the ISHE and IASHE mechanisms have the same contributions for the detection of electrically and thermally generated magnons.

8.5.10 Finite non-local signal in the fully perpendicular case ($\phi = 89^\circ$)

In Fig. 4(a) of the main text, the precise location where the magnons are generated/extracted at the Py/YIG interface is not important. However, in Fig. 4(b) of the main text, particularly in the fully perpendicular case of $\phi = 89^\circ$, magnons are expected to be generated/extracted only at the two (lateral) edges of the Py injector/detector, with the edge width determined by the spin relaxation length in Py ($\approx 5$ nm). Therefore, there are only two relevant locations at the injector and at the detector contacts, as depicted in Fig. 8.15. If all the four edges (the two edges of the injector and the two edges of the detector) equally contribute to the magnon injection/extraction process, the net signal should be zero. However, as we know from non-local magnon transport experiments [9], for these injector-detector distances, the signal scales inversely with the distance. Therefore, the non-local signal will be dominated by the closest locations of the injector and the detector, which are the two inner edges (the right edge of the injector and the left edge of the detector), as shown.

Figure 8.14: The second harmonic (2f) response measured by the Py detector at $\phi = 0^\circ$, when the contribution due to the ANE is negligible. The magnons generated via the SSE are electrically detected by the Py nanowire via the combination of the ISHE and the IASHE, as shown.
in Fig. 8.15 This leads to the finite non-local signal measured at $\phi = 89^\circ$, which is not cancelled out by the contribution from the outer edges.

**References**


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