Chapter 4

Frequency and power dependence of spin-current emission by spin pumping in a thin-film YIG|Pt system

Abstract

This chapter presents the frequency and power dependence of spin pumping in a ferrimagnetic insulator|normal metal system. The used system consists of a ferrimagnetic insulating thin film of yttrium iron garnet (YIG, 200 nm) grown by liquid-phase epitaxy coupled with a normal metal with a strong spin-orbit coupling (Pt, 15 nm). The YIG layer presents isotropic behavior of the magnetization in the plane, a small linewidth ($\alpha \approx 2 \times 10^{-4}$), and a surface roughness less than 0.4 nm. Shown in this chapter is the dependency of the voltage signal from the spin-current detector on the frequency (0.6–7 GHz), the microwave power $P_{in}$ (1–70 mW), and the applied in-plane static magnetic field. A strong enhancement of the spin-current emission is observed at low frequencies, showing the appearance of nonlinear phenomena.

4.1 Introduction

The actuation, detection, and control of the magnetization dynamics and spin-currents in hybrid structures (magnetic material|normal metal) by using the (inverse) spin-Hall effect (ISHE and SHE), spin-transfer torque (STT), and spin pumping, has attracted much attention in the last few years. The observation of these phenomena in ferromagnetic (FM)|normal metal (NM) systems has been reported by several groups [1–4].

Spin pumping is the generation of spin-currents from magnetization precession, which can be excited by microwave radiation (microstrip [5], resonant cavity [6], waveguide [7]). In a FM|NM system, this spin-current is injected into the NM layer, where it is converted into a dc electric voltage using the ISHE. In 2010, Kajiwara et al. [6] opened new interest in this research-field by the demonstration of the spin pumping/ISHE and SHE/STT processes in a system using the magnetic insulating material yttrium iron garnet (YIG, 1.3 µm), coupled with a thin layer of platinum (Pt, 10 nm). It has been shown experimentally that the combination of these materials...
and the mentioned phenomena can be used to transmit electrical information over several millimeters [6, 8, 9]. The insulator-normal metal (YIG|Pt) system presents an important role for future electronic devices related to nonlinear dynamics effects [10–14], such as active magnetostatic wave delay lines and signal-to-noise enhancers, and bistable phenomena [15].

In this chapter, spin-current emission in a YIG (200 nm)|Pt (15 nm) structure as a function of microwave frequency \( f \), microwave power \( P_{\text{in}} \), and applied in-plane magnetic field \( B \) is presented. The actuation of the spin-current emission is provided by a nonresonant 50 \( \Omega \) microstrip transmission line\(^1\) within a range of \( f \) between 0.6 and 7 GHz. To the best of our knowledge, in all previously reported experiments, the thickness of the single-crystal of YIG, grown by liquid-phase epitaxy (LPE), is within a range of 1.3–28 \( \mu \)m, which is always higher than the exchange-correlation length defined in pure YIG [11]. In contrast, the thickness of the YIG used for the experiments presented here is only 200 nm.\(^2\) Experiments with lower thickness of YIG have been reported [16, 17], however, these layers are grown by different methods than LPE. The different growing processes result in an enhancement of the linewidth and these layers do not reach the high quality as when grown by LPE.

Besides its thickness, two other points should be made concerning our YIG sample. First, the in-plane magnetic field dependence of the magnetization presents isotropic behavior and second, no stripe domains have been observed by magnetic force microscopy (MFM).

### 4.2 Experimental details

#### 4.2.1 Sample description

Spin pumping experiments in FM|NM systems for different NM materials have been performed in order to study the magnitude of the dc voltage induced by the ISHE [18]. It has been shown that the mechanism for spin-charge conversion is effective in metals with strong spin-orbit interaction. Therefore, for the experiments presented in this chapter, Pt is used as the normal metal layer. As the magnetic layer, the insulating material \( Y_3Fe_5O_{12} \) (YIG) is used. The sample is based on a layer of single-crystal \( Y_3Fe_5O_{12} \) (YIG) (111), grown on a (111) \( Gd_3Ga_5O_{12} \) (GGG) single-crystal substrate

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\(^1\)The characteristic impedance of the microstrip is designed with respect to the source impedance. By taking into account the geometric dimensions of the line, the electrical properties of the line (Au), and the permittivity of the substrate (alumina) we have realized a microstrip line with an impedance of 50 \( \Omega \). In order to create a maximum current through the microstrip and therefore a maximum coupling (in the frequency range that we have used), the end of the transmission line has been shorted.

\(^2\)Investigation of high quality thin YIG films is beneficial for possible applications, as thinner YIG allows for miniaturization of devices, it simplifies the application of nanolithography techniques and for example because the spin transfer torque is inversely proportional to the thickness of the magnetic layer.
4.2. Experimental details

Figure 4.1: (a), (b) Schematics of the experimental setup for spin pumping measurements. The ferromagnetic resonance in the YIG is excited by using a microstrip line in reflection between 0.6 and 7 GHz. The thickness of the YIG and the GGG substrate is 200 nm and 500 µm, respectively. Ti|Au electrodes are attached on top of the Pt layer in order to detect the generated ISHE voltage. The magnetic field \( B \) is applied in the plane of the sample along the \( \hat{x} \)-direction and \( B \perp h_{rf} \), where \( h_{rf} \) is the microwave field. (c) In-plane magnetic field dependence of the magnetization \( M \) (normalized by the saturation magnetization \( M_s \)) of the pure single-crystal of YIG, performed by VSM at room temperature.

The thickness of the YIG is only 200 nm, which is very low compared to other studies [6, 11, 12, 19, 20]. The YIG layer has a roughness of 0.4 nm. X-ray diffraction was used in order to estimate the quality of the thin layer of YIG. The spectrum (not shown) shows epitaxial growth of YIG oriented along the (111) direction with zero lattice mismatch.

For the realization of the device structure, two steps of lithography have been used. First, to create the Pt layer (15 nm thick), an area of 800 × 1750 µm² has been patterned on top of a YIG sample (1500 × 3000 µm²), by electron-beam lithography (EBL). Before deposition of the Pt layer by dc sputtering, argon etching has been used to clean the surface. Etching was done during 5 seconds at a beam voltage (intensity) of 500 V (14 mA) with an acceleration voltage of 200 V. The second lithography step realizes the 100-nm-thick Ti|Au electrodes having a width of 30 µm. For both lithography steps, poly(methyl methacrylate) (PMMA) with a thickness of 270 nm has been used as resist. A schematic of the final device is shown in Fig. 4.1(b).

4.2.2 Static and dynamic magnetization characterizations

By using specific growing conditions, the anisotropic contributions (growth and magneto-elastic) in the YIG film can be optimized in order to keep the magnetization in-plane. Fig. 4.1(c) shows the dependence of the YIG magnetization as a function of the applied in-plane magnetic field, as measured by using a vibrating sample magnetometer (VSM) at room temperature. The saturation magnetization
\( \mu_0 M_s = 0.176 \text{ T} \), corresponding to the value obtained for YIG in bulk [6, 11]. The low coercive field (\( \approx 0.06 \text{ mT} \)) and the shape of the hysteresis loop provide an easy prove of the magnetization being in the plane, with a very low dissipation of the energy. VSM measurements along the two crystallographic axes, [1,\( \overline{1} \),0] and [1,1,\( \overline{2} \)], show similar responses indicating isotropic behavior of the magnetization in the film plane. In addition, no stripe domains have been observed by MFM.

In order to well characterize the pure single-crystal of YIG, before realizing the YIG|Pt structure, broadband ferromagnetic resonance (FMR) measurements have been performed using a highly sensitive wideband resonance spectrometer in the perpendicular configuration (the applied magnetic field \( B \), is normal to the film plane). The microwave excitation is provided with a nonresonant 50 \( \Omega \) microstrip reflection line within a range of microwave frequencies between 2 and 25 GHz. The FMR is measured via the first derivative of the power absorption \( dP/dH \) by using a lock-in measurement technique. The value of the modulation field (lock-in reference) used during the field sweeping is much smaller than the FMR linewidth. The dependence of the frequency resonance \( \omega_{\text{res}} \) as a function of the resonant magnetic field is used to determine the gyromagnetic ratio \( \gamma = 1.80 \times 10^7 \text{ rad T}^{-1} \text{ s}^{-1} \) (and the Lande factor, \( g = 2.046 \)). The intrinsic Gilbert damping parameter is extracted from the dependence of the linewidth as a function of the microwave frequency (\( \alpha \approx 2 \times 10^{-4} \)) [21].

### 4.2.3 Spin pumping measurements

For the actuation of the magnetization resonance in the YIG layer the YIG|Pt device is placed as shown in Fig. 4.1(a). In this configuration, the microwave field \( h_{\text{rf}} \) is perpendicular to the static magnetic field \( B \). To optimize the electric voltage recording, a lock-in detection technique was used. The modulation frequency generated by the lock-in, is sent to the network analyzer trigger. This command (with a frequency of 17 Hz) controls the modulation of the microwave field, generated by the network analyzer (see also section 3.2). The microwave field is periodically switched on and off between \( P_{\text{rf}}^{\text{high}} \) and \( P_{\text{rf}}^{\text{low}} \), respectively. \( P_{\text{rf}}^{\text{low}} \) is equal to 0.001 mW and \( P_{\text{rf}}^{\text{high}} \) corresponds to the input microwave power, so-called in the following, \( P_{\text{in}} \). The dc voltages generated between the edges of the Pt layer are amplified and detected as a difference of \( V(P_{\text{rf}}^{\text{high}}) - V(P_{\text{rf}}^{\text{low}}) \).

Using this measurement setup, the dependence of the electric voltage signal as a function of the microwave power (1–70 mW) and microwave frequency (0.6–7 GHz) is analyzed, while sweeping the applied static magnetic field \( B \). \( B \) is large enough in order to saturate the magnetization along the plane film. All measurements were performed at room temperature.
4.3 Results and discussion

4.3.1 Detection of the ISHE signal

Conversion of spin-currents into electric voltage via the ISHE is given by the relation [6] \( \vec{E}_{\text{ISHE}} \propto \vec{\sigma} \times \vec{J}_s \), where \( \vec{E}_{\text{ISHE}} \) and \( \vec{\sigma} \) are the electric field induced by the ISHE and the spin polarization, respectively. In a YIG\|Pt system, the origin of the spin-current \( J_s \) injected into the Pt layer differs from the conventional spin-current in conducting systems such as Py\|Pt. Here the spin pumping originates from the spin exchange interaction between localized magnetic moments in YIG at the interface and conduction electrons in the Pt layer.

A typical curve showing the magnetic field dependence of the voltage signal in YIG (200 nm)\|Pt (15 nm) is shown in Fig. 4.2 (for \( F = 3 \) GHz and \( P_{\text{in}} = 20 \) mW). The sign of the electric voltage signal is changed by reversing the magnetic field along \( \hat{x} \) and no sizable voltage is measured when \( B \) is swept parallel to \( \hat{y} \), as expected [6]. The reversal of the sign of \( V \) (by reversing the magnetic field) shows that the measured signal is not produced by a possible thermoelectric effect, induced by the microwave absorption. A direct measurement of the electric voltage signal (without lock-in amplifier) has been performed in order to define the absolute sign of \( V_{\text{ISHE}} \) as a function of the magnetic and electric configuration. The voltage detected between

![Image of Figure 4.2: Dependence of the electric voltage signal \( V_{\text{ISHE}} \) as a function of the magnetic field \( B \), for the YIG (200 nm)\|Pt (15 nm) sample. \( B \) is applied in-plane, along \( \hat{x} \). The inset shows \( V_{\text{ISHE}} \) at resonant condition \( B_{\text{res}} \) for the positive and negative configurations of the magnetic field [along \( +\hat{x} \) and \( -\hat{x} \), respectively; see Fig. 4.1(b)].]
the edges of the Pt layer shows resonance-like behavior, with a maximum value ($\Delta V$) at the resonant condition $B_{\text{res}}$ of the system, as defined in the inset of Fig. 4.2.

### 4.3.2 Frequency and power dependence of the ISHE signal

In Fig. 4.3 the in-plane magnetic field dependence of the electric voltage signal for a large range of microwave frequencies between 0.6 and 7 GHz is shown. For each value of microwave power ($P_{\text{in}} = 1, 10, \text{ and } 20 \text{ mW}$) the voltage signal $V_{\text{ISHE}} = f(P_{\text{in}}, f)$ at resonant conditions has been extracted and plotted. To the best of our knowledge, only two groups [6, 11] have studied the electric voltage signal in a YIG|Pt system as a function of microwave frequency, and only one [11] in a large frequency range of (2−6.8 GHz). The difference between our structure and Ref. [11] lies in the thickness of the YIG, which is 1.3 µm in their case and only 200 nm in this work. The thickness of the Pt is the same (15 nm). As can be seen from Fig. 4.3, the frequency dependence of $\Delta V$ presents a complicated evolution, partly resulting from the $S_{11}$ dependence of the microstrip in reflection itself, as a function of fre-

![Figure 4.3: Dependence of the electric voltage signal $V_{\text{ISHE}}$ for the YIG (200 nm)|Pt (15 nm) sample as a function of the static in-plane magnetic field, within a microwave frequency range of 0.6−7 GHz, at 20 mW. The symbols correspond to the values of $\Delta V$ for different microwave powers: 1, 10, and 20 mW.](image-url)
4.3. Results and discussion

frequency. Nevertheless we note that $\Delta V$ presents the most high values at the lower frequencies.

Figs. 4.4(a)−4.4(c) present the dependence of the electric voltage $V_{\text{ISHE}}$ as a function of the magnetic field and the microwave power for different frequencies (1, 3, and 6 GHz, respectively). In those spectra multiple resonance signals are present, broadening the observed peaks. In the observed spectra this broadening is attributed to the magnetostatic surface spin waves (MSSW, $B < B_{\text{res}}$) and backward volume magnetostatic spin waves (BVMSW, $B > B_{\text{res}}$) [22, 23]. Furthermore, at low frequency [$F = 1$ GHz, shown in Fig. 4.4(a)] a strong nonlinear dependence is observed, which is represented by a shift in resonance magnetic field, as a function of power, combined with asymmetric distortion of the resonance line. These observations are correlated with the pioneering works of Suhl [24] and Weiss [25] related to nonlinear phenomena occurring at large precession angles. The simple expression of the magnetization precession cone angle at resonance is given by $\Theta = h_{\text{rf}}/\Delta H$ [26], where $h_{\text{rf}}$ and $\Delta H$ correspond to the microwave magnetic field and the linewidth of the absorption line of the uniform mode, respectively. For lower frequencies $\Delta H$ is smaller as compared to higher frequencies, and therefore this expression shows that by decreasing the excitation frequency, an enhancement of the cone angle is induced. This means that the system becomes more sensitive to the RF microwave power, $P_{\text{in}}$.

In addition, the nonlinear behavior measured at 1 GHz (also at 3 GHz, but less) is well represented by Fig. 4.4(d). This figure represents evolutions of $\Delta V$ as a function of the microwave power $P_{\text{in}}$, performed at 1, 3, and 6 GHz between 1 and 70 mW. Kajiwara et al. [6] have proposed an equation to represent the dependence of the electric voltage signal as a function of $B$, $f$, $h_{\text{rf}}$, and the parameters of the bilayer system. They showed that $V_{\text{ISHE}}$ at resonant conditions depends linearly on the microwave power. This dependence is well reproduced only at 6 GHz. Fig. 4.4(e) represents the ratio of $\Delta V$ extracted from measurements at 1 and 6 GHz, $\Delta V_{1\text{GHz}}/\Delta V_{6\text{GHz}}$, as a function of the microwave power $P_{\text{in}}$, to emphasize the nonlinearity observed at 1 GHz. Note that, for a very low microwave power of 1 mW, $\Delta V$ at 1 GHz is 14 times greater than $\Delta V$ at 6 GHz, whereas by increasing $P_{\text{in}}$, this difference is drastically reduced and reached a factor of 5 at 60 mW.

4.3.3 Nonlinear behavior at low frequencies

To investigate the frequency dependence of $\Delta V$, the response of the microstrip line should be taken into account. For example, in Fig. 4.3 a peak in $V_{\text{ISHE}}$ is observed between 30 and 40 mT and between 70 and 100 mT. These peaks can be ascribed to an artificial increase of $V_{\text{ISHE}}$ induced by the microstrip line. The correction factor for this artificial increase is determined by measuring the reflection parameter $S_{11}$, for the system being out of resonance.
Fig. 4.4: (a), (b), and (c) present the dependence of the electric voltage signal $V_{\text{ISHE}}$, as a function of the static magnetic field $B$, for different microwave power $P_{\text{in}}$, at 1, 3, and 6 GHz, respectively. (d) Representation of $\Delta V$ as a function of the microwave power between 1 and 70 mW at 1, 3, and 6 GHz. The inset corresponds to the dependence of $\Delta V$ for low RF power. (e) Microwave power dependence of the ratio of the values of $\Delta V$ measured at 1 and 6 GHz.

Fig. 4.5(a) represents the frequency dependence of $\Delta \tilde{V}/P_{\text{in}}$, where $\Delta \tilde{V}$ corresponds to the the dc voltage corrected by the response of the microstrip line itself. This figure permits one to define the frequency range in which this evolution presents nonlinear behavior. Note that between 3.4 and 7 GHz, values of $\Delta \tilde{V}/P_{\text{in}}$ present a slow decrease as a function of the microwave frequency. In this regime, $\Delta \tilde{V}/P_{\text{in}}$ values are similar for the different RF microwave powers of 1, 10, and 20 mW, due to the fact that in this frequency range the RF power dependence of $\Delta V$ is linear [6, 13]. The interesting feature of the frequency dependence of $\Delta \tilde{V}/P_{\text{in}}$ is observed at frequencies below 3.4 GHz. At those frequencies, the frequency dependence does not follow the same trend as observed at higher frequencies ($>3.4$ GHz). In the frequency range (0.6–3.4 GHz), the previously observed nonlinear behavior affects the values of $\Delta \tilde{V}/P_{\text{in}}$ as a function of the input RF microwave power.
The enhancement $\Delta \tilde{V}/P_{in}$ is more efficient at low powers and gradually reduces with increasing the microwave power. The discrepancy is especially strong around 1 GHz. Kurebayashi et al. [11] obtained 17.1 and 62.8 nV/mm at 2 and 6 GHz, respectively, whereas in our system, for the same frequencies, $\Delta V$ reaches 542.85 and 108.6 nV/mm (for this comparison, the signals are normalized by the length of the Pt strip).

The question arising now: What is the origin of the strong enhancement of $\Delta \tilde{V}/P_{in}$ at low frequency? Is it only due to the frequency dependence of the cone angle? The assumption of a single magnetization precession angle is not warranted, due to the fact that several spin-wave modes contribute to the dynamic response of the system.

![Graph](image)

**Figure 4.5:** (a) Dependence of $\Delta \tilde{V}/P_{in}$ as a function of the microwave frequency with a microwave power of 1, 10, and 20 mW. The red dashed line corresponds to the analytical expression of the frequency dependence of $\Delta V$ extracted from Ref. [6]. (b) Dependence of the resonance frequency $f$, as a function of the applied magnetic field. Open circles indicate the experimental data for $k \perp B$ (in-plane magnetic field) and the solid black curve is calculated from Kittel’s equation (Ref. [27]) given by $f = \sqrt{f_H(f_H + f_M)}$, with $f_H = \gamma \mu_0 H$ and $f_M = \gamma \mu_0 M_s$. The red solid and dotted lines show the minimum possible resonance frequencies for a thick and a thin (200-nm-thick) YIG layer, respectively. The blue lines present the corresponding minimal needed frequencies for the three-magnon splitting process to be allowed (c) Dispersion relation of spin waves, calculated using Ref. [28]: dependence of the frequency as a function of the wave-vector $k$, when $k \parallel B$ for different thicknesses of YIG. The magnetic field is fixed at 40 mT.
Therefore, the normalization of $\Delta V$ by $\Theta$ (defined by $\alpha$) and $P$ is not sufficient to explain the enhancement of $\Delta \tilde{V}/P_{\text{in}}$ at low frequency. Here, $P$ corresponds to the correction factor related to the ellipticity trajectory of the magnetization precession of the uniform mode [29] due to the magnetic field configuration (in-plane).

The analytical expression [red dashed line in Fig. 4.5(a)] extracted from Ref. [6], in which the spin-current at the YIG|Pt interface is defined by the uniform mode, cannot reproduce the $\Delta \tilde{V}/P_{\text{in}}$ behavior at low frequency. As reported previously in Refs. [11] and [12], the low-frequency behavior can be attributed to the presence of nonlinear phenomena. Kurebayashi et al. [11] demonstrated the possibility to control the spin-current at the YIG|Pt interface by three-magnon splitting. This nonlinear phenomenon can be easily actuated for very low RF power [30]. Kurebayashi et al. [11] observed that the threshold power of the splitting in their system was around 18 $\mu$W, which is very low with respect to the RF power used for FMR and dc voltage measurements.

The three-magnon splitting induces the creation of two magnons (with short wavelength) from the uniform mode (long wavelength), following the equations $f = f_1 + f_2$ and $k = k_1 + k_2$, where $f$ and $k$ are the frequency and wave vector with $f_1 = f_2 = \frac{1}{2} f$ and $k_1 = -k_2$ [22, 30]. In agreement with Kurebayashi et al. [11], we observed a strong enhancement of $\Delta \tilde{V}/P_{\text{in}}$ at low frequency, nevertheless this dependence does not necessarily mean that three-magnon splitting is involved in our system. By following the schema of the three-magnon splitting process, one finds that this phenomenon is allowed for only a specific frequency range, dependent on the YIG thickness.

The black dots and line in Fig. 4.5(b) show the experimental dependence of the resonance conditions of our sample and a fit calculated from Kittel’s equation, respectively. From this plot we can find whether the three-magnon splitting process is likely to be present in our system. For a thick sample of YIG the lowest possible FMR frequency $f_{\text{min}} \approx f_H$, where $f_H$ is the Larmor frequency [red solid line in Fig. 4.5(b)]. As the FMR frequency cannot be lower than $f_H$ [31], the excitation frequency should be higher than $2f_H$ [blue solid line in Fig. 4.5(b)] in order that the three-magnon splitting process can take place, as is described by the above equations. Consequently, the upper frequency limit $f_{\text{cutoff}}$, for the three-magnon splitting to take place, for a thick sample system of YIG, is $f_{\text{cutoff}} = \frac{2}{3} f_M$, where $f_M = \gamma \mu_0 M_s$, which follows from Kittel’s equation.

In the experiment of Kurebayashi et al. [11], they have used a YIG sample with a thickness of 5.1 $\mu$m, which is higher than the exchange correlation length, and therefore in their case $f_{\text{min}} \approx f_H$. In our case the YIG thickness is only 200 nm, and the dependence of $f_{\text{min}}$ [red dotted line in Fig. 4.5(b)] is very different from $f_H$ [red solid line in Fig. 4.5(b)]. The blue dotted line shows the values of $2f_{\text{min}}$, which gives...
the minimum excitation frequency needed for the three-magnon splitting to take place in this thin YIG sample. It can be seen that this line does not cross the black curve, which shows the possible excitation frequencies of our system. This suggests that the three-magnon splitting process is not allowed in our case.

Another check of the possible presence of the three-magnon splitting is by calculating the spin-wave spectrum in YIG, which is shown in Fig. 4.5(c), when the magnetic field is parallel to the wavevector \( k \), for different thicknesses of YIG [28]. The calculation has been performed with a magnetic field of 40 mT inducing a microwave frequency \( f = 2.66 \) GHz with \( \gamma = 1.80 \times 10^7 \) rad T\(^{-1}\) s\(^{-1}\). The minima of the shown BVSWM dispersion curves (\( f_{\text{min}} \)) result from the competition between the dipole interaction and the exchange interaction. A crossing of the dispersion curve with the black dotted line (\( f/2 \)) shows that the three-magnon splitting process is allowed. By reducing the thickness, the minimum frequency increases. For thin layers of YIG, the dispersion curve does not cross the black dotted line anymore, indicating that here the three-magnon splitting is no longer allowed.

The role of the three-magnon splitting process for the spin pumping is not fully clear, and there are more phenomena which can induce the creation of spin waves with short-wavelength (like other multi-magnon processes such as four-magnon and two-magnon scattering). For example, it has been shown by Jungfleisch et al. [14] that the two-magnon process (due to the scattering of magnons on impurities and surfaces of the film) contributes to the enhancement of the spin-current at the YIG\( |\)Pt interface.

The strong enhancement of \( \Delta V \) observed at low frequency is due to the fact that the dc voltage induced by spin pumping at the YIG\( |\)Pt interface is insensitive to the spin-wave wavelength [11, 14]. In other words, \( \Delta V \) is not only defined by the uniform mode but also from secondary spin-wave modes, which present short wavelength. Nevertheless, it is not obvious to identify the contributions of the different multi-magnon processes to the observed enhancement of the dc voltage at low frequency.

### 4.4 Conclusion

In summary, we have shown spin-current emission in a hybrid structure YIG (200 nm)\( |\)Pt (15 nm) as a function of microwave frequency \( f \), microwave power \( P_{\text{in}} \), and applied in-plane magnetic field \( B \). At low frequency, a strong enhancement of the voltage signal across a spin-current detector of Pt was observed. This behavior can be understood if we assume that the measured signal is not only driven by the FMR mode (which contributes to the spin pumping at the YIG\( |\)Pt interface), but also from a spectrum of secondary spin-wave modes, presenting short wavelengths.
In YIG-based electronic devices, the creation of short-wavelength spin waves is considered as a parasitic effect. However, in this case it can be used as a spin-current amplifier. Before integrating this system in a device, many questions related to the contribution for the spin pumping of the spin waves with short wavelength should be solved. By choosing a specific thickness range, it should be possible to follow the contribution of the three-magnon splitting ($f_{\text{cutoff}}$) by a combination of Brillouin light scattering [11] and spin pumping measurements. More details of other multi-magnon processes should be given by temperature dependence measurements. Nevertheless, due to the observed enhancement of $\Delta V$ in the frequency range (0.6–3.2 GHz), YIG|Pt devices could be further downscaled, still keeping detectable signals. The isotropic behavior of the in-plane magnetization, the absence of stripe domains, and the high-quality thin layer of YIG (200 nm) grown by liquid-phase epitaxy give keys to success in this way.
Bibliography


4. Spin-current emission by spin pumping in a thin-film YIG/Pt system


Bibliography


