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Control of propagating spin-wave attenuation by the spin-Hall effect

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The spin-Hall effect induced modification of the attenuation of propagating exchange-mode spin waves (SWs) is studied micromagnetically and analytically in heavy-metal/ferromagnet bilayers. Micromagnetic simulations of spin-wave propagation in Pt/NiFe show that at a relatively low current density of \( \sim 6 \times 10^{11} \text{ A/m}^2 \), Gilbert damping is exactly balanced by the spin-Hall torque and long-distance SW transmission is possible. An analytical model is developed to explain the micromagnetic results and relate the current density to the characteristic attenuation length. The results suggest that the spin Hall effect can be used as an effective means to control the attenuation length of propagating spin waves in nanostructures. Published by AIP Publishing.

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I. INTRODUCTION

Spin waves (SWs) are the collective spin excitations in a magnetic material. They are of great fundamental and technological interest due to their central role in magnetization dynamics and the possibility to exploit them for signal transmission and processing in spintronic devices.(-13) Low-damping alloys\(^1\)\(^-\)\(^3\) and garnet films\(^4\)\(^-\)\(^6\) have provided model systems for examining SW phenomena and devices due to the large SW attenuation length in these materials. However, many recent modeling efforts have focused instead on metallic ferromagnets, in which the very short wavelength of dipole-exchange mode spin waves (DESWs) makes them better-suited for nanoscale magnonic devices.\(^7\)\(^-\)\(^9\) It has been shown through micromagnetic simulations that nanostructured metallic ferromagnets can be engineered to act as spin-waveguides and magnonic crystals for signal interconnects,\(^10\) filtering,\(^11\) and logic.\(^12\)\(^-\)\(^13\) Moreover, SWs can interact with magnetic domain walls,\(^14\)\(^-\)\(^17\) allowing for hybrid spintronic architectures combining information storage and transmission capabilities.\(^17\) Unfortunately, realizing such devices experimentally is challenging due to the relatively large damping in transition metal ferromagnets, which limits the attenuation length to typically a few micrometers or less.

Recent micromagnetic studies have demonstrated SW amplification using non-adiabatic spin-transfer torque (STT) generated by spin-polarized current flowing through a metallic ferromagnet.\(^18\) Current-induced SW amplification could be used to counter intrinsic damping and enhance the propagation distance of SWs in devices, while also adding new functionality. However, significant amplification was only predicted at extremely high current densities with a large nonadiabicity parameter,\(^18\) which may be difficult to achieve experimentally. More recently, the spin torque from the spin Hall effect (SHE) in nonmagnetic heavy metals (HMs) such as Pt,\(^19\)\(^-\)\(^21\) Ta,\(^21\)\(^-\)\(^22\) and W\(^23\) has been shown capable of exciting magnetization dynamics and large-amplitude switching in an adjacent ultrathin FM when a relatively low current density flows parallel to the interface. This effect produces a Slonczewski-like antidamping torque\(^24\)\(^,\)\(^25\) that can counteract damping and drive the magnetization away from equilibrium. Using optical and electrical measurement techniques, several early experiments have proved that the Slonczewski-like torque induced by the SHE could indeed modulate the amplitude of propagating dipole SWs in HM/ferromagnet bilayers such as Pt/CoFeB,\(^26\) Ta/CoFeB,\(^27\) Pt/ YIG,\(^28\) and Pt/Pt.\(^29\)

In this work, we first show through micromagnetic simulation that the SHE is sufficient to provide a practical means to achieve current-controlled amplification/attenuation of DESWs as was studied experimentally in Refs. 26–29. Moreover, we reveal that the SHE-driven torque can exactly balance the Gilbert damping at a certain critical current density, leading to extremely long-range propagation of SWs. Finally, using an analytical approach, we develop a simple equation for the effective SW attenuation length in such HM/ferromagnet bilayers under the influence of the SHE, which can be used to engineer the properties of propagating SWs in magnonic devices.

II. SIMULATION METHODS

A Pt/Ni\(_{80}\)Fe\(_{20}\) bilayer, similar to that experimentally studied in Ref. 29, was chosen as a typical heavy-metal/ferromagnet bilayer for these studies. We considered a nanostrip geometry, shown schematically in Fig. 1(a), in which a charge current flowing parallel to the interface generates a vertical spin current with incident spin polarization along the \( y \)-axis. The ratio of vertical spin-current to in-plane charge current is given by the spin Hall angle, \( \theta_{SH} \). This spin current exerts a Slonczewski-like torque \( \tau_{SHE} \) on the ferromagnet of the form

\[
\tau_{SHE} = \gamma \tilde{m} \times \left( \hbar \theta_{SH} \frac{\mu_0 e M_s L_z}{2 \mu_0 e M_s L_z} \tilde{m} \times \hat{y} \right).
\]
Here, $j_0$ is the charge current density, $M_s$ is the ferromagnet saturation magnetization, $L_z$ is the ferromagnet thickness, $e$ is the electron charge, $\gamma$ is the gyromagnetic ratio, $\mu_0$ is the vacuum permeability, $\hbar$ is the reduced Planck constant, and $\tilde{m} = M/M_s$ is the normalized magnetization. We used a spin-Hall angle $\theta_{SH} = +0.07$, corresponding to the value for Pt reported in Ref. 19.

Magnetization dynamics was examined by incorporating this torque into the Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{\partial \tilde{m}}{\partial t} = \gamma \tilde{m} \times \vec{H}_{\text{eff}} + \alpha \tilde{m} \times \frac{\partial \tilde{m}}{\partial t} + \tilde{m}_{\text{SLT}},$$

(2)

where $\alpha$ is the Gilbert damping constant and $\vec{H}_{\text{eff}}$ is the net effective field, including applied, exchange, anisotropy, and dipolar fields.

We first examine the effect of current injection on SW propagation through micromagnetic simulations. Simulations were performed for a $2 \mu$m long, 30 nm wide, 1 nm thick Ni$_{80}$Fe$_{20}$ strip, using the Object Oriented Micromagnetics Framework (OOMMF) with the cell size of $2.5 \times 2.5 \times 1$ nm$^3$. The materials parameters were chosen to be those of Permalloy ($\alpha = 0.01$, exchange constant $A = 1.3 \times 10^{-11}$ J/m, and $M_s = 8 \times 10^5$ A/m). Vertical spin current injection by the SHE was implemented in OOMMF by using a second ferromagnetic spin polarizing layer magnetized along $+x$, with vertical current flow, and with current densities scaled so that the spin current corresponds to what would be generated by the current densities reported here when flowing in a Pt layer with the specified spin Hall angle. Note that the damping constant of 0.01 used for convenience in this simulation, which is known as the typical damping constant of Py thin films, might be too small for such an ultrathin Py layer placed in contact with Pt, due to spin pumping enhancement of the damping. However, it is possible experimentally to insert spin-transparent layers between Pt and the ferromagnet to reduce this effect or use a different spin Hall metal such as Ta, which has been found not to increase the effective damping of the ferromagnet it is in contact with. Moreover, the exact value of the damping constant only influences the results quantitatively without affecting on the main idea emphasized throughout this study. Due to the form of the Slonczewski-like torque, the transverse spin polarization of the SHE-generated spin current will tend to amplify or damp local precessional motion about $\vec{y}$ due to SW excitations. We therefore imposed an in-plane transverse anisotropy (which is localized to the Py layer) so that the magnetization orients along $\vec{y}$ in equilibrium and thus injected current can maximally amplify or attenuate SWs. A relatively large anisotropy field $H_k = 10$ kOe was used to ensure saturation along the transverse direction for convenience, but in practice, a static transverse bias field could be used to ensure a significant component of the magnetization along $\vec{y}$.

III. RESULTS AND DISCUSSION

SW amplification was studied by using a SW source consisting of a row of cells at the left-end of the nanowire excited by a time-varying field $H_x = H_0 \sin(2\pi \nu t)$, where $H_0 = 10$ kOe and $\nu = 100$ GHz. Such a large field amplitude of $H_0 = 10$ kOe was chosen to effectively perturb the...
magnetization of Py, since a strong anisotropy field of $H_K = 10\, \text{kOe}$ was used. This sine cardinal function serves to equally excite all modes of SWs up to \( \nu \), so that the spectral dependence of current-induced effects can be examined. While this excitation was applied, a dc-current through the Pt layer was simulated by injecting a spin current vertically proportional to \( \theta_{\text{SH}} \) (as described above). Figures 1(b)–1(d) show the Fast Fourier transform (FFT) of the \( z \)-component (out of plane) magnetization within the entire area of nanowire computed for a time interval of 2 ns after the external Oersted field was applied. Excitation spectra are shown for dc-currents corresponding to \( j_{\text{DC}} = -1 \times 10^{12} \, \text{A/m}^2 \), \( j_{\text{DC}} = 0 \), and \( j_{\text{DC}} = +1 \times 10^{12} \, \text{A/m}^2 \), respectively. The parabolic relation between the frequency (\( f \)) and the wave vector (\( k \)) is observed in all cases, corresponding to the dispersion relation of dipole-exchange mode SWs. A lower cutoff frequency near \( f \sim 15\,\text{GHz} \), which appears due to the lowest transverse standing wave mode \( k_y \) in a confined geometry, is also observed. Note that our geometrical configuration falls in the Damon-Eshbach36 geometry where the SW wave vector is perpendicular to the magnetization of Py. However, the Damon-Eshbach SWs, which are dominated by dipolar interactions that exhibit a linear dispersion relation for small wave numbers and disappear as the exchange-dominated SWs from the Heisenberg interaction emerge at larger wave numbers,37,38 are not observed in our SW spectrum. The SWs from the Heisenberg interaction emerge at larger wave numbers and disappear as the exchange-dominated SWs may arise near nanowire edges because the restricted geometry induces strongly localized low-f SW modes in the excitation spectrum as studied in Refs.39 and 40. This is reasonable because SWs can propagate to the end of nanowire while maintaining large amplitude at \( j_{\text{DC}} = 6 \times 10^{11} \, \text{A/m}^2 \), implying sizable SW-edge interactions. Figure 2(e) shows the SW amplitude versus distance at various current densities. It is clear that current injection along the nanowire significantly enhances or reduces the SW attenuation length depending on the current polarity, consistent with a current-induced (anti)-damping-like torque. With no applied current, the intensity of SWs is reduced exponentially by a factor of \( \sim 100 \) at \( d = 2 \, \mu\text{m} \). However, with \( j_{\text{DC}} = 6 \times 10^{11} \, \text{A/m}^2 \), the SHE-driven effective torque exactly balances the Gilbert damping and the SW intensity is maintained at the same level along the \( 2 \, \mu\text{m} \) length. This negligible SW attenuation is also in good agreement with the simulation result presented in Fig. 2(d). At \( j_{\text{DC}} > +6 \times 10^{11} \, \text{A/m}^2 \), the SW attenuation becomes negative, and therefore the SW amplitude exponentially grows and the uniformly-magnetized state is destabilized further along the nanowire, causing chaotic magnetization dynamics as described in more detail below.

In order to provide further insight into spin-Hall torque-induced spin-wave attenuation, here we provide a simple analytical relation. From a similar approach used in Ref. 18, where the nonadiabaticity of the spin transfer torque was considered as an additional torque term within the LLG equation, we can draw a simple relation for our case, where the spin Hall torque is considered instead of a nonadiabatic torque. With the assumption of small damping, the SHE-induced modulation of spin wave attenuation length becomes

$$
\lambda \propto \frac{1}{\omega \tau_{\text{SH}} - \Pi \omega},
$$

(3)

where \( \lambda \) is the characteristic attenuation length, \( \tau_{\text{SH}} \) is the angular frequency, and \( \Pi \) is the constant coefficient of a Slonczewski-like torque as shown in Eq. (1), where
\[ \Pi = \frac{\Delta \phi_j}{\Delta M_{SW}}. \]

Because the term \( \Delta \phi_j \) implies the SW relaxation rate in the presence of damping, Eq. (3) represents the spin-Hall current-induced change of the SW attenuation length, which is reasonably expected and also analytically studied in Ref. 29. Because the term \( \Pi \) is directly proportional to the spin Hall angle, \( \eta_{SH} \), it is evident that the SHE can compensate the intrinsic damping and thus can modulate the SW attenuation. Moreover, the attenuation length diverges when \( \phi_j = \Pi j_c \), and this state can be achieved by increasing the current density at a given frequency of SWs and the spin Hall angle. In Fig. 2(d), we have observed that SHE can exactly compensate the Gilbert damping near \( j_{DC} = 3 \times 10^{11} \) A/m², and this state can be achieved by increasing the current density at a given frequency of SWs and the spin Hall angle. In Fig. 2(d), we have observed that SHE can exactly compensate the Gilbert damping near \( j_{DC} = 3 \times 10^{11} \) A/m² and the critical current density using the derived equation, where \( \phi_j = \Pi j_c \), and \( j_c = +6 \times 10^{11} \) A/m², which agrees with the simulation result.

In Fig. 2(d), we extract the attenuation length from the micromagnetically computed SW amplitude versus position as \( \frac{\Delta \phi_j}{\Delta M_{SW}} = -\frac{1}{\lambda} \), where \( A_{SW} \) is the amplitude of propagating SWs. In Fig. 3, we plot these data versus current density, as well as the analytical result for \( -1/\lambda \) using Eq. (3). Figure 3 shows good agreement between the full micromagnetic calculations and the analytical result, indicating that Eq. (3) captures the essential physics responsible for SHE-induced SW attenuation.

With \( j_{DC} > j_c \), a negative attenuation length can be estimated from Eq. (3), corresponding to amplification of the SW amplitude with increasing distance from the SW source as seen in Fig. 2(d). In this case, chaotic magnetization dynamics ensues distant from the SW source, and with increasing time, the transition to chaotic dynamics moves progressively towards the SW source. Figures 4(a) and 4(b) show micromagnetic snapshots with increasing time after applying Oersted field to excite SWs to the left, in the case of zero current density and \( j_{DC} > j_c \), respectively. It is evident that the negative attenuation predicted for \( j_{DC} = +1 \times 10^{12} \) A/m² above a threshold indeed drives a transition to chaotic dynamics. In detail, the superposition between the propagating SWs from the source and reflected SWs from the right edge of the nanowire leads to local standing waves...
within the nanowire structure. As time evolves, the amplitude of the local standing SWs becomes much stronger, and eventually overtakes the entire structure, eventually turning into random domain nucleation and expansion. Figures 4(c) and 4(d) show the Fast Fourier transform (FFT) of the z-component (out of plane) magnetization as a function of wave number and wire position, respectively. It is first obvious that strong local low-frequency SW modes, which should be forbidden due to the geometrical confinement, are observed for the chaotic dynamics. The low-frequency modes, which were also shown in Fig. 2(d), correspond to the local SWs arising from the edges, and Fig. 4(d) indeed exhibits the evolution of strong low-frequency modes from the wire edge, where the interaction between forward and backward SWs is the strongest. This behavior suggests that SWs may likewise play an important role in SHE-induced switching, since they tend to destabilize the uniform state and can be amplified by the switching current.

IV. CONCLUSION

In conclusion, micromagnetic simulations predict DESW amplification and attenuation driven by the SHE torques at relatively low current density using spin Hall angles that are readily achieved with known spin Hall metals. Analytical modeling gives a simple expression for the SW attenuation length dependence on current density and spin Hall angle, which reproduces well the full micromagnetic results. These results show that the spin Hall torque can be harnessed for SW amplification, allowing for a means to overcome damping for long-distance SW signal transmission and providing an electrical means to control SW devices.

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