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Parametric excitation of magnetization oscillations controlled by pure spin current

E. R. J. Edwards[1], H. Ulrichs[1], V. E. Demidov[1*], S. O. Demokritov[1], and S. Urazhdin[2]

[1]*Institute for Applied Physics and Center for Nonlinear Science, University of Muenster, Corrensstrasse 2-4, 48149 Muenster, Germany*

[2]*Department of Physics, Emory University, Atlanta, GA 30322, USA*

We report an experimental investigation of parametric excitation of magnetization oscillations in a Permalloy microdisk in the presence of a pure spin current. The latter is generated by an adjacent Pt layer due to the spin Hall effect. We demonstrate that the spin torque induced by the pure spin current can significantly reduce the threshold for the parametric instability, and modify the frequency range of the parametrically excited oscillation at a given pumping power. Our results show that pure spin currents can be utilized for stimulation and control of nonlinear dynamic magnetic phenomena in microscopic structures.

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* Corresponding author, e-mail: demidov@uni-muenster.de

Spin current – the flow of angular momentum associated with the electron's spin – is an essential ingredient of spin-based electronic (spintronic) devices. Spin currents have been historically tied to the charge currents of spin-polarized electrons, and thus required a conducting path through the device. It was recently shown that a pure spin current not accompanied by a charge current can be generated due to the spin Hall effect (SHE).[1,2] Pure spin currents do not require a conducting path, providing an opportunity for the development of previously inaccessible spintronic device geometries.[3-12] For instance, a fully planar geometry became possible in devices utilizing spin currents for control of magnetization dynamics in both metallic and insulating ferromagnets, enabling direct access to the active device area for studies by advanced magnetooptical techniques such as micro-focus Brillouin light scattering (BLS) spectroscopy.[13] Devices operated by pure spin currents are also less susceptible to the effects of heating and electromigration (see, e.g., recent reviews Ref. 14,15 and references therein).

By utilizing pure spin currents, electronic control of the effective magnetic damping,[3-6] reduction of high-frequency magnetic noise,[7] excitation and amplification of propagating spin waves,[8-10] and magnetization switching[11,12] have been demonstrated. In addition to technical applications, the ability to controllably vary the dynamic magnetic damping by pure spin currents also provides a unique opportunity for the experimental investigations of nonlinear dynamic magnetic phenomena. In particular, it is well known that the onset of nonlinear behaviours in magnetic systems depends not only on the amplitude of the dynamic magnetization, but also on its relaxation characteristics.[16] Therefore, variation of the effective damping by spin current can provide a mechanism for the stimulation of nonlinear behaviours and for controlling their characteristics.

The parametric instability[16-19] stands out among the nonlinear dynamic magnetic phenomena due to its extensive practical applications, in particular in amplification and generation of high-frequency magnetization oscillations and waves. Although the efficiency of the parametric excitation is typically smaller than the direct linear excitation, this method enables excitation of dynamic modes and short-wavelength spin waves which are difficult to excite directly. This method also represents a powerful experimental tool, for example, in studies of magnon Bose-Einstein condensates.[20,21] The parametric instability has been extensively studied in macroscopic magnetic systems.[16-18] However, much less is known about this phenomenon in microscopic systems.[22-24]

Here, we report an experimental investigation of the parametric spin-wave instability in a microscopic magnetic system that consists of a Permalloy microdisk fabricated on top of a Pt microstrip. The latter serves as a source of the microwave field as well as an injector of a pure spin current generated by the spin Hall effect in Pt. Parametric instability in the microdisk cannot be achieved at reasonable power levels of the microwave pumping signal in the absence of spin current due to the relatively strong damping. We show that the instability threshold can be significantly reduced by injecting spin current with appropriate polarization, resulting in the onset of the parametrically induced oscillations. We also demonstrate that the characteristics of the instability region can be controlled over a wide range by varying the dc current in the Pt line. Moreover, we show that by analyzing the temporal evolution of the parametrically induced oscillations, the spin current-dependent relaxation characteristics of microscopic magnetic structures can be directly determined.

The schematic of the experiment is shown in Fig. 1. A 10 nm thick Pt film fabricated by e-beam lithography into a 2.4 μm wide stripe is connected to Au microwave transmission lines. A $Ni_{80}Fe_{20}$ =Permalloy (Py) disk with a 2 μm diameter and 5 nm thickness is fabricated on top of the Pt line. It is separated from the latter by a 2 nm thick Cu spacer to avoid detrimental effects of Pt on damping in Py.[5] The electrical resistance of the structure was 30 Ohms.

The microwave magnetic field for the parametric excitation was produced by a microwave current applied to the Pt line simultaneously with a dc current I. Because of the SHE, a pure spin current flows from Pt into Py and exerts a spin-transfer torque (STT) on its magnetization.[1-3]

In our experiment, both microwave and dc currents were applied in short pulses to reduce the Joule heating. The dc current pulses were 500 ns-long, while the microwave pulses were 100 ns-long and their start was delayed relative to the start of the dc pulses by 300 ns. The pulse repetition period was 2 μs. Under these conditions, microwave power of up to 50 mW and dc current of up to 25 mA could be applied without sample degradation.

The static magnetic field H=900 Oe was applied in the plane of the sample, perpendicular to the direction of current in the Pt line. In this configuration, the dynamic magnetic field **h** created by the microwave current in the Pt line is collinear with the static field. Consequently, the dynamic field does not directly excite the magnetization dynamics. Instead, this field produces a periodic modulation of the total instantaneous magnetic field, resulting in a modulation of the eigenfrequency of magnetic oscillations[25]. By analogy with the parametric resonance in mechanics,[26] the modulation of the parameters of the system with the frequency f_p results in a reduction of the effective magnetic damping[16-19] of the magnetization oscillations at the frequency $f_p/2$. The damping can be completely compensated at a sufficiently large applied microwave power, resulting in the onset of magnetization oscillations at the frequency $f_p/2$. This phenomenon is known as parametric instability. Since the parametric instability requires a complete compensation of damping, it can develop only above a certain threshold value of the pumping power P_{th} determined by the relaxation characteristics of the system. The central idea of our experiment is to test the possibility to control the characteristics of parametric instability by varying the effective magnetic damping by a pure spin current.

The parametrically excited magnetization dynamics was detected by micro-focus BLS.[13] The probing laser light was focused into a diffraction-limited spot at the center of the Py disk, yielding a signal proportional to the square of the amplitude of dynamic magnetization at this location. The spectral resolution of this technique is better than 50 MHz, and the temporal resolution is 1 ns when measuring response to pulsed microwave excitation.

The initial measurements were performed without a dc current (at I=0). Under these conditions, no parametric instability was observed for pumping powers P up to the maximum used value of 50 mW, suggesting that the parametric excitation threshold determined by the dynamic damping in Py is too high. Subsequent measurements were performed at finite values of I, for both directions of dc current I. At I>12 mA, clear signatures of the parametric instability were detected. For the selected orientation of H, the instability was observed only at I>0, as expected for the effects of spin current that reduce the effective magnetic damping. From the symmetry of SHE,[1-3] one can expect that $I<0$ increases the effective damping. Indeed, no instability was observed at $I<0$.

Figure 2 shows an example of the spectra of parametrically excited oscillation for different levels of the pumping power P, at I=20 mA. The spectra were recorded by varying f_p from 14 to 18 GHz with a 100 MHz step size, and simultaneously recording the BLS intensity proportional to the square of the amplitude of dynamic magnetization at the frequency $f=f_p/2$. The measured spectra exhibit a resonant behavior slightly below the ferromagnetic resonance (FMR) frequency of the Py disk f_{FMR}=8.49 GHz, which was separately measured in the standard FMR geometry. The lowering of the resonant frequency with respect to f_{FMR} is caused mainly by the reduction of the static magnetization due to the effects of the spin current, and by the Oersted field of the dc current in the Pt line.[7] With increasing P, the resonant peak shifts toward lower frequencies, broadens, and becomes noticeably asymmetric. These nonlinear behaviors are typical for the parametric resonance.[23]

The dependence of the parametrically induced oscillation spectra on the microwave power for I=15, 20, and 25 mA is summarized in three color-coded plots in Fig. 3. The white circles in these plots mark the boundaries of the instability region for the given pumping power, which are defined by the condition that the oscillation intensity falls below 5% of the maximum detected value. The width of the instability region decreases with the decrease of the pumping power P, and vanishes when P approaches the threshold value P_{th} determined by the dynamic magnetic damping in the Py microdisk. Comparing the spectra acquired at different I, we conclude that P_{th}

decreases with increasing I, as expected due to the reduction of the effective damping induced by the spin current.

The quantitative characteristics of the observed spectra are detailed in Fig. 4. As illustrated in Fig. 4(a), the threshold power P_{th} decreases by about a factor of 4 when I is increased from 15 to 25 mA. The threshold power is extrapolated to increase above 50 mW at I<10 mA. These data demonstrate that parametric instability cannot be achieved in the studied system at reasonable pumping power levels without injection of spin current, in agreement with our qualitative observations. The frequency f_0 at the onset of the parametrically excited oscillations decreases approximately linearly with increasing I, suggesting that this variation is dominated by the Oersted field of the current in the Pt line. The value f_0=8.5 GHz obtained by extrapolating this dependence to I=0 is in excellent agreement with the independently determined f_{FMR}=8.49 GHz. Therefore, we can conclude that the parametrically excited mode in the studied system is the quasi-uniform FMR mode of the Py microdisk.

Figure 4(b) shows the dependence of the frequency f_{max} of the maximum oscillation intensity on the microwave pumping power. As P is increased above P_{th}, f_{max} initially remains constant, and then starts to decrease. This redshifting is likely caused by the reduction of the static magnetization of Py due to the increasing intensity of the parametrically excited magnetization oscillations.

Figure 4(c) shows the dependence of the frequency range Δf of the parametrically excited oscillations on the pumping power, at different values of I. These data demonstrate that in addition to enhancing the parametric instability, the spin current can significantly change the frequency range of the instability at a given pumping power.

For example, as I is varied from 15 to 25 mA at P=50 mW, Δf increases from 0.3 to 0.8 GHz, i.e. by more than a factor of 2.

The stationary measurements of the parametric instability described above provide evidence for the effect of spin current on the effective damping in Py. To characterize this effect quantitatively, we directly determined the spin current-dependent effective relaxation rate by measuring the temporal evolution of the parametrically excited magnetization oscillations in response to a pulsed microwave pumping signal.

Figure 5(a) shows on the logarithmic scale the temporal evolution of the BLS intensity after the start of the microwave pumping pulse at t=0, at different pumping power levels. The initial exponential increase of intensity is characterized by a time constant that decreases with increasing pumping power. This dependence can be attributed to the increasing efficiency of the parametric amplification, producing an effect similar to negative damping of magnetization oscillations. As a result, at $P>P_{th}$ the amplitude grows exponentially at a rate[19,23] $\gamma = C\sqrt{P} - \omega_r$, where the term $C\sqrt{P}$ characterizes the parametric amplification, ω_r is the relaxation frequency, and C is a constant. In agreement with the theory, the measured dependencies $\gamma\left(\sqrt{P}\right)$ are linear [Fig. 5(b)]. By extrapolating these dependencies to P=0, it is straightforward to find the relaxation rates for different values of the current I, as shown in Fig. 5(c). We note that the relaxation rate in the studied system linearly decreases with increasing current over the entire range of I=15-25 mA, i.e., the observed effect of spin current is consistent with the linear modification of the effective damping by the spin transfer mechanism. Therefore, we can conclude that the established theoretical models predicting linear modification of the damping are also applicable when considering complex nonlinear magnetic dynamic phenomena.

In conclusion, we demonstrated that injection of pure spin currents provides an efficient mechanism for control of the parametric instability in microscopic magnetic structures. Our findings open advanced routes for basic studies of nonlinear magnetization dynamics on the microscopic scale, as well as for applications of nonlinear magnetic phenomena in spintronic devices. They demonstrate that pure spin currents can play a significant role in dynamic phenomena in magnetism, which may find important applications in spin-based electronics.

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[25] Note that the microwave current in the Pt line additionally creates an alternating spin current periodically modulating the damping in the Py disk, which can also contribute to the parametric excitation. However, this contribution is not expected to

be significant, since the magnitude of the microwave current is at least by one order of magnitude smaller than the dc current needed to produce a sizable effect on the damping.

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FIGURE CAPTIONS

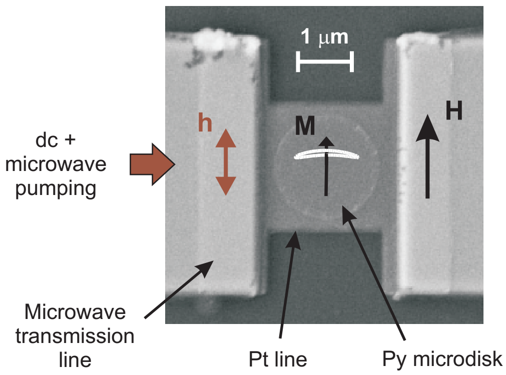
Fig. 1 (color online) Schematic of the experiment.

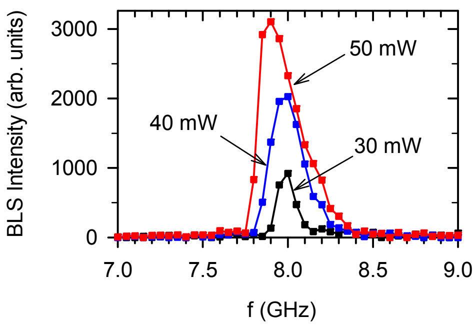
Fig. 2 (color online) Typical spectra of parametrically excited magnetization oscillations for different levels of the pumping power, as indicated. The data were obtained at I=20 mA.

Fig. 3 (color online) Psudocolor-coded dependencies of the BLS intensity on the frequency $f=f_p/2$ and the pumping power P at I=15, 20, and 25 mA, as labeled. Open white circles in the graphs mark the boundaries of the instability region. Lines are guides for the eye.

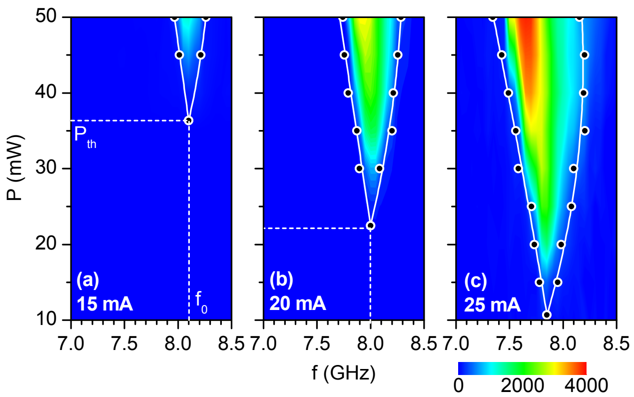
Fig. 4 (color online) (a) The threshold pumping power P_{th} and the frequency f_0 of the parametrically excited magnetization oscillations at the onset of the parametric instability vs. current. Lines are guides for the eye. (b) The frequency of the maximum intensity of the parametrically excited magnetization oscillations vs. the pumping power, at the labeled values of I. Curves are guides for the eye. (c) The frequency range of the parametrically excited oscillation vs. pumping power, at the labeled values of I. Curves are guides for the eye.

Fig. 5 (color online) (a) Log-linear plot of temporal evolution of the BLS intensity after the start of the microwave pumping pulse at t=0, at the labeled levels of the pumping power. The data were obtained at I=20 mA. The curves are the results of fitting of the experimental data by exponentials. (b) The rate of the oscillation amplitude increase vs. parametric pumping power, at the labeled values of current I. Lines show the results of the linear fitting of the experimental data. (c) Relaxation frequency vs. current. The line is a linear fit of the data.

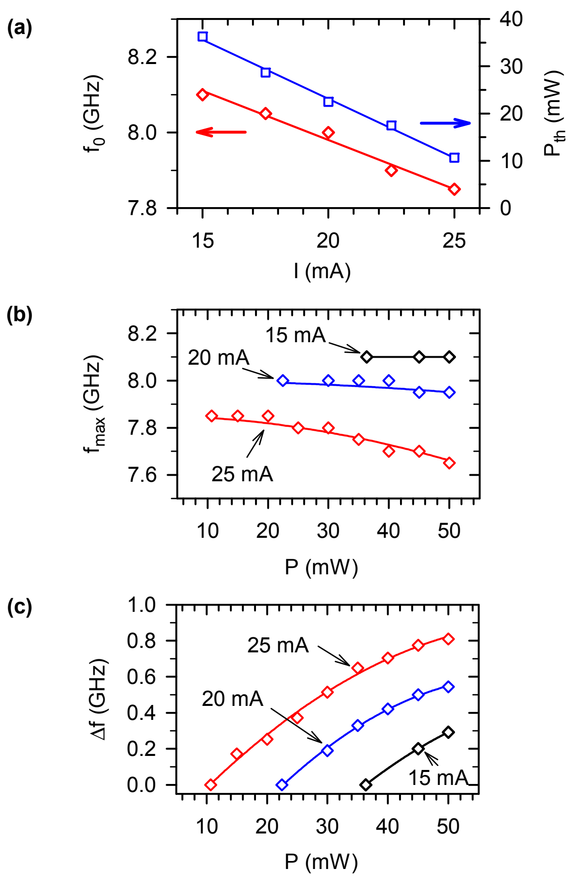

1 μm
h
M
H
dc +
microwave
pumping
Microwave
transmission
line
Pt line
Py microdisk



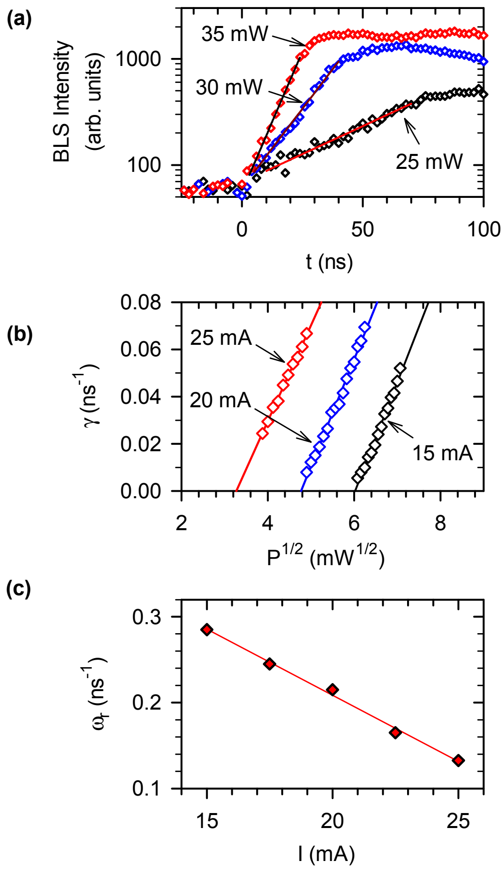
BLS Intensity (arb. units)
3000
2000
1000
0
7.0
7.5
8.0
8.5
9.0
f (GHz)
50 mW
40 mW
30 mW



P (mW)
f (GHz)
(a)
15 mA
(b)
20 mA
(c)
25 mA
P_th
f_0
0
2000
4000



(a)
8.2
8.0
7.8
f_0 (GHz)
40
30
20
10
0
P_{th} (mW)
15
20
25
I (mA)
(b)
15 mA
20 mA
25 mA
8.2
8.0
7.8
7.6
f_{max} (GHz)
10
20
30
40
50
P (mW)
(c)
1.0
0.8
0.6
0.4
0.2
0.0
Δf (GHz)
25 mA
20 mA
15 mA
10
20
30
40
50
P (mW)


(a)
35 mW
30 mW
25 mW
BLS Intensity (arb. units)
1000
100
0
50
100
t (ns)
(b)
25 mA
20 mA
15 mA
γ (ns^-1)
0.08
0.06
0.04
0.02
0.00
2
4
6
8
P^1/2 (mW^1/2)
(c)
ω_r (ns^-1)
0.3
0.2
0.1
15
20
25
I (mA)