Coherent Suppression of Magnetization Precession in Presence of Spin Waves in a Ni$_{81}$Fe$_{19}$ Microwire

Anjan Barman$^{1,2}$, T. Kimura$^{2,3}$, Y. Fukuma$^2$, and Y. Otani$^{2,3}$

$^1$Department of Physics, Indian Institute of Technology Delhi, New Delhi 110016, India
$^2$RIKEN ASI, Wako, Saitama 351-0198, Japan
$^3$Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan

In this paper, we present the coherent suppression of precessional dynamics in a Ni$_{81}$Fe$_{19}$ (permalloy) microwire of 12-μm width and 100-μm length in presence of multiple spin-wave modes. The lateral confinement of the microwire causes spin-wave modes of frequencies very close to each other and local suppression of the modes were experimentally achieved with field pulses of slightly different durations but with the same rise time and fall time. Analysis shows that application of the pulsed field causes a large angle reorientation of the magnetization followed by a precession. The termination of the pulsed field at around 500 ps causes the magnetization to return back to the equilibrium position and to align parallel to the effective field so that the torque on the magnetization vanishes. However, this applies only to localized regions due to the presence of spin-wave modes of slightly different frequencies. Pulses of slight under or overlap cause the precession to continue at a slightly different frequency suggesting that the spin-wave modes are not truly localized but there are overlapping regions where one mode dominates. When the dominating mode is partially suppressed, the relative amplitude of the modes changes significantly and the overall power spectrum peaks at a slightly different frequency.

Index Terms—Magnetization dynamics, micromagnetic simulations, spin waves, time-resolved magneto-optical Kerr effect.

I. INTRODUCTION

MAGNETIZATION dynamics is a topic of intense interest due to their multifaceted output to the scientific and technological communities. Magnetic data storage [1], nonvolatile memories [2], logic devices [3], [4], spin transistors, and field effect transistors (FETs) [5] are directly linked with the magnetization processes that occur at various time scales.

One of the principal interests in this area is the precessional switching which has the potential to change the switching time drastically. Several reports have appeared on the coherent precessional switching [6]–[8] and coherent suppression of precession [9]–[12] in magnetic structures of micrometer and submicrometer length scales but the contradictory results suggested that the physical shape and size of the samples have a major role in this area and the question arises whether it is possible to suppress the precessional dynamics in presence of multiple spin-wave modes by a simple pulse-shaping scheme [11].

Magnetization dynamics of rectangular-shaped samples of various width over length ratios have been studied extensively and the lateral confinement along the width and length of the samples resulted in number of standing and propagating spin waves [13]–[17]. The dispersion of spin waves has been studied in detail and effects such as size and shape dependence of precession frequency, anisotropic damping, and dynamic configurational anisotropy have been observed [15]. Here we present an effort to understand the coherent suppression of precessional dynamics in such systems in presence of multiple spin waves that has not been studied in detail. We have used experimental results and micromagnetic simulations from a permalloy microwire of 12-μm width, 100-μm length, and 50-nm thickness and demonstrated that the coherent suppression may be achieved by slightly varying pulselength along the width of the microwire.

II. EXPERIMENTAL

The time-resolved dynamics and the coherent suppression experiments have been performed by a home-built benchtop time-resolved magneto-optical Kerr microscope which is described in detail elsewhere [18]. An electronic pulse generator generates an ultrafast magnetic field pulse on the sample deposited on a microstrip line structure (100-nm thick Au on GaAs) by launching a voltage pulse into the microstrip line with nominal rise time (10%–90%) of 55 ps, fall time (90%–10%) of 115 ps, and variable duration (full width at half maximum) from 100 ps to 10 ns and maximum magnitude of ±10 V. The permalloy sample is fabricated on the microstrip line by sputtering and e-beam lithography. The measured rise time, fall time, and amplitude of the transmitted pulse through the microstrip line by a 20-GHz sampling oscilloscope are 60 ps, 120 ps, and 95%, respectively, without any significant ringing or reflection. The precession of magnetization induced by the ultrafast magnetic field pulse is probed by measuring the magneto-optical Kerr rotation of a linearly polarized laser as a function of the time delay between the optical and electronic pulses. A pulsed injection diode laser with central wavelength of 408 nm, pulselength ~42 ps, spectral width ~7 nm, and average power ~5 μW is focused down to a submicrometer spot on the sample to probe the dynamics. The sample is scanned under the focused laser spot by a piezoelectric scanning stage to measure the position-dependent time-resolved magnetization traces.

Manuscript received March 03, 2009. Current version published September 18, 2009. Corresponding author: A. Barman (e-mail: abarman@physics.iitd.ac.in).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

This paper comes with supplementary downloadable material available at http://ieeexplore.org.

Digital Object Identifier 10.1109/TMAG.2009.2023995
III. RESULTS AND DISCUSSIONS

The time-resolved longitudinal Kerr rotation is measured with the bias magnetic field applied along the long axis and the pulse field applied along the short-axis of the microwire as shown in Fig. 1(a). The bias field dependence of precession frequency is studied with the probe spot placed at the center of the sample and fitted with the Kittel formula for the ferromagnetic resonance frequency to obtain the magnetic parameters for the sample [18]. Fig. 1(b) shows the time-resolved magnetization and the corresponding fast Fourier transform (FFT) spectra performed over the whole experimental time range (0–4 ns), using a Welch window, when the probe spot is placed at the center and two other positions on the short axis of the microwire. A pulse field with duration $\Delta T_p = 1$ ns and peak amplitude of 80 Oe and a bias field of 20 Oe are applied in the geometry as shown in Fig. 1(a). The pulsed field causes a large angle reorientation of the in-plane magnetization from the long axis which appears as a large initial step followed by a ringing corresponding to the precession of magnetization. When the probe spot is placed at 2 and 4 μm away from the center on the short axis of the microwire, the precession parameters change, which is clear from the partial suppression of a small precession period at the falling edge of pulses of identical duration. The variation of precession frequency is not clear in the corresponding FFT spectra due to the broadening of the peaks. Further, a low-frequency peak in the FFT spectra is observed due to the shape of the pulse itself, whose position varies with the variation of pulse duration.

Fig. 2 shows the time-resolved magnetization for a series of values when the probe laser is located at the center of the short-axis of the microwire. When $\Delta T_p$ is larger or smaller than 535 ps, ringing corresponding to the precession of magnetization appears to a varying extent in the time-resolved signal. However, when $\Delta T_p = 535$ ps the precession is completely stopped by the falling edge of the pulse field and only a step-like magnetization as a function of time is observed with fast rise time and fall time. The FFT spectra give additional evidence for the suppression of ringing as shown in lower panels of Fig. 2. The mode centered at 2.3 GHz is observed clearly for 4 ns and remains the dominant mode down to 550 ps. However, as $\Delta T_p$ decreases, the peak power decreases and peak width increases indicating a partial suppression of the precession. When $\Delta T_p = 535$ ps, the peak at 2.3 GHz completely disappears in the FFT spectra. When $\Delta T_p$ is varied below 535 ps, a broad peak centered at 2.1 GHz appears with a shoulder at
2.3 GHz, which becomes increasingly prominent as $\Delta T_p$ becomes smaller. When the probe spot is placed 2 $\mu$m away from the center, the precession is suppressed for $\Delta T_p = 485$ ps although traces with $\Delta T_p = 500$ ps and 475 ps are almost identical to that for $\Delta T_p = 485$ ps. For all other pulse durations, precession is observed. However, the peak frequency at 2.3 GHz for $\Delta T_p = 4$ ns increases monotonically to 2.5 GHz as $\Delta T_p$ gradually reduces to 510 ps and the peak power gradually reduces. As $\Delta T_p$ is reduced further below 485 ps, the precession appears again in the time-resolved traces and the peak at 2.3 GHz appears in the FFT spectra. The peak power and peak width gradually increase as $\Delta T_p$ decreases. When the probe spot is placed at 4 $\mu$m away from the center, the precession is completely suppressed for $\Delta T_p = 512$ ps. When $\Delta T_p$ decreases from 4 ns to 525 ps, the peak in the FFT spectra shifts gradually from 2.3 to 2.5 GHz. However, as $\Delta T_p$ decreases from 500 ps to 475 ps, the peak reduces further to 2.1 GHz and then remains constant.

The above observations indicate that there must at least be three spin-wave modes with frequencies centered around 2.1, 2.3, and 2.5 GHz. The peaks in the FFT spectra observed at different positions of the microwire for various pulse durations are a superposition of these modes. While detailed investigation of the spatial character of the above modes is beyond the scope of this paper, it appears that there are regions of spatial overlap of these modes. Since the mode frequencies are very close to each other, a range of pulse field duration around 500 ps is able to either completely or partially suppress these modes. Consequently, the peak of the FFT spectra shifts towards the frequency that is less suppressed compared to other frequencies. At any particular position on the sample where the dominant mode is fully suppressed other modes may continue to precess with small amplitude.

IV. MICROMAGNETIC SIMULATIONS

To understand the dynamics and the mechanism of coherent suppression we have performed time-dependent micromagnetic simulations of the microwire using object oriented micromagnetic framework (OOMMF) [19]. The sample was divided into a 2-D array of cuboidal cells with dimension 25 nm $\times$ 25 nm $\times$ 50 nm. The cell size is significantly larger than the exchange length of permalloy but that does not affect our result since the inhomogeneous dynamics observed is dominated by the long range dipolar field. The bias field and the pulse fields are applied in the same geometry and of same amplitude as used in the experiment. The magnetic parameters used in the simulation are typical values for permalloy. Fig. 3(a) shows the time-dependent in-plane magnetization components ($M_x$ and $M_y$) averaged over the sample volume for various $\Delta T_p$ values. This clearly shows that when $\Delta T_p$ is between 470 and 530 ps the precession is fully or nearly suppressed over the whole sample volume with the optimum result at $\Delta T_p = 500$ ps. This is consistent with the experimental observation where the local suppression of precession at various positions occurred for similar values of $\Delta T_p$. In order to investigate the position dependence of the coherent suppression, we have simulated the time-dependent magnetization ($M_x$ and $M_y$) at $\Delta T_p = 500$ ps within a 1 $\mu$m$^2$ area at the center of the element, 2 $\mu$m away from the center, and 4 $\mu$m away from the center as shown in Fig. 3(b). The traces at the center and 4 $\mu$m away from the center continue to precess while for the trace at 2 $\mu$m away from the center, the precession is almost suppressed after the pulse is switched off. Simulations of local magnetization show a higher frequency component, which is absent in experimental traces due to larger noise level than the amplitude of this mode.

The simulated time-resolved images at selected time delays ($t$) for $\Delta T_p = 400, 500$, and 600 ps are shown in Fig. 4. The simulations were performed on the entire microwire but here we have presented only a section of 10- $\mu$m length at the center of the microwire. Until $t = 500$ ps, the dynamics for all pulse durations is the same. At $t = 0$, a uniform magnetization is observed along the long axis of the microwire except for small nonuniform edge regions. The pulsed field shifts the effective magnetic field from the long axis to the vicinity of the short axis of the wire. Consequently, the magnetization rotates by a large angle from the long axis. A large amplitude precession about the effective field takes the magnetization further away towards the direction opposite to the bias field. A maximum deflection of about 135° is observed at 300 ps. Until $t = 400$ ps, the dynamics is coherent over the major part of the microwire except for narrow edge regions. At $t = 500$ ps, the magnetization except the edge regions points towards the initial magnetization state during precession. During the falling edge of the pulsed field, the effective magnetic field rotates from the vicinity of the short axis to the original direction of the long axis, while the precession continues about the effective magnetic field unless at
any instant the magnetization suddenly becomes parallel to the effective field and the torque vanishes. For $\Delta T_p = 400$ ps, the falling edge of the pulse is too early (between 460 and 580 ps) and hence the magnetization continues to precess even after the effective field returns back to its original direction. When $\Delta T_p = 600$ ps, the falling edge is too late (between 660 and 780 ps), which allows the magnetization to precess back towards the short axis (hard axis) when the effective field shifts towards the original direction of the long axis (easy axis). The magnetization becomes unstable and a nonuniform dynamics is established for time delays between 900 and 2500 ps and remains for the simulation duration of 4 ns. This could be a calculation artefact due to the large mesh size that cannot take into account properly a Neel wall whose natural core is of the order of the exchange length. When $\Delta T_p = 500$ ps, the falling edge lies between 560 and 680 ps, i.e., when the magnetization over the entire microwire except for small edge regions points towards the initial direction. The magnetization follows the effective field, which rotates back to the initial direction. At a position close to the initial direction, the magnetization becomes parallel to the effective field, the torque vanishes, and precession stops coherently. There is a slight overshoot of precession at the center and out-of-phase precession near the edges parallel to the short axis but those die down quickly. For pulse fields with $\Delta T_p$ between 470 and 530 ps, similar behavior is observed but the optimum result is obtained for $\Delta T_p = 500$ ps.

V. Conclusion

In summary, we have observed a coherent suppression of precession in presence of nonuniform dynamics in a permalloy microwire. Experiment shows a position dependence of the required pulse field duration for the coherent suppression, which is consistent with the slight variation of the precession frequency with position along the short axis of the microwire. For pulse durations above and below the required value of pulse duration for coherent suppression, ringing occurs with varying amplitude, which is also clear from the FFT spectra. We have reproduced this behavior by time-dependent micromagnetic simulations, which provided additional insight to the coherent suppression mechanism. Simulated time-resolved images show that for an undershoot or overshoot of the pulse duration the magnetization does not become parallel to the effective field during the falling edge of the pulse and attains a new and unstable precessional state. However, for a specific range of pulse duration around 500 ps the above condition is satisfied and the precession stops coherently.

Acknowledgment

This work was supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (S).

References