Nonreciprocal emission of spin-wave packet in FeNi film

K. Sekiguchi,[1,a)] K. Yamada,[1] S. M. Seo,[2] K. J. Lee,[2] D. Chiba,[1] K. Kobayashi,[1] and T. Ono[1]
[1]*Institute for Chemical Research, Kyoto University, Uji 611-0011, Japan*
[2]*Department of Materials Science and Engineering, Korea University, Seoul 136-701, Republic of Korea*

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We report a time-resolved propagating spin wave spectroscopy for $Fe_{19}Ni_{81}$ film. We show that the amplitude of the spin-wave packet depends on the direction of magnetization and that its phase can be controlled by the polarity of pulsed magnetic field for the excitation. The nonreciprocal emission of spin-wave packet can be utilized for the binary spin-wave input into the spin-wave logic circuit. © *2010 American Institute of Physics*. [doi:10.1063/1.3464569]

Spin-wave-based devices for signal processing have been of great interest for the spintronic integrated circuits (ICs) in virtue of ultrafast propagation and low power consumption.[1–3] The spin-wave logic gates have been recently demonstrated by using the Mach–Zehnder interferometer with yttrium iron garnet (YIG) waveguides.[3] Since the YIG is not compatible with standard silicon integrated circuit (IC) technology, spin wave propagation in IC-compatible materials such as FeNi is such of importance for the realization of ICs.[4–13]

In FeNi film, the magnetostatic surface wave (MSSW) is the promising mode due to its large propagation velocity and a nonreciprocal character which was also observed a long time ago in YIG films.[3–5] So far, it was intensively investigated by using frequency domain spectroscopy[9–11] and microfocused Brillouin light scattering (BLS) (Refs. 4, 7, and 12) methods.

In this letter, we report on nonreciprocal emission of spin-wave packet in FeNi thin film in time domain. We show that the amplitude of spin wave depends on the direction of magnetization and that the phase of spin wave can be controlled by the polarity of pulsed magnetic field for the excitation.

We performed a time-resolved propagating spin wave spectroscopy,[13–16] for the microfabricated device comprising $Fe_{19}Ni_{81}(35\ \text{nm})/SiO_2(35\ \text{nm})$ film with 120 μm width [see Fig. 1(a)]. An external magnetic field ($H_y \sim 100$ Oe) magnetizes the permalloy film in the y direction so that the spin waves can propagate in the MSSW mode. Spin waves are excited and detected with a pair of asymmetric coplanar strip (ACPS) transmission lines placed on the film. The detail geometry of ACPS is depicted in Fig. 1(b). For the time-resolved measurement of spin wave dynamics, we launch a voltage pulse V_{ex} into the left ACPS with 5 ns duration in 100 kHz reputation frequency, causing a pulsed field, h_{pulse}, which generates spin-wave packet. The spin wave with the wave vector k induces a voltage on the right ACPS connected to a 20 GHz sampling oscilloscope or 8 GHz real-time oscilloscope. The signal of spin wave with $-k$ can be detected by launching a voltage pulse into the right strip and connecting the oscilloscope to the left strip. The present study was performed by measuring a set of devices in which the gap distance g between the two ACPSs varies from 5 to 50 μm. To improve the signal to noise ratio, we used a background subtraction procedure[13–17] and took the average of 1024 waveforms to produce a single spin wave signal.

Figure 2(a) represents the induced voltages in the detection strip antenna for the samples with different gap distances, signaling the spin-wave packets. The envelopes of packets are well characterized by the Gaussian function $y = A\exp[-(t-t_0/\tau)^2]$ where A is the amplitude, t_0 center of packet, and τ the decay time. With increasing g, the packet represents a propagating decay and delay characterized by A and t_0, respectively. In the inset of Fig. 2(a), the A and t_0 are plotted as a function of g, showing an exponential decay and a linear delay. A spin wave attenuation length Λ is estimated to be $\Lambda = 15\ \mu$m by the exponential fitting using the formula $A\exp(-x/\Lambda)$. A group velocity is determined to be 13 136 m/s from the linear slope of the delay.

The spin-wave packet can be excited by four different excitation configurations: (M,k), $(-M,k)$, $(M,-k)$, and $(-M,-k)$. Here, $-M$ is set by applying the external magnetic field H_y along the $-y$ direction. The frequency-bias field relation (f-H) was investigated for all the excitation configurations. As shown in Fig. 2(b), the f-H relations are identical for all configurations. The experimental data are well explained by using the theoretical MSSW dispersion relations:

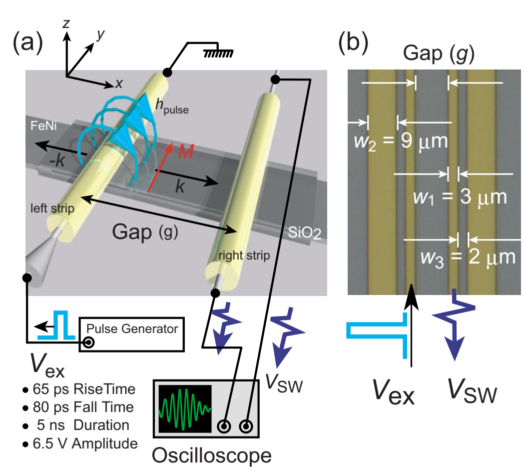

FIG. 1. (Color online) Schematic of time-resolved measurements of spin wave packet. A spin wave packet is excitated and detected with a pair of ACPS with a gap distance g. (b) Optical micrograph of ACPSs comprising a signal line ($w_1 = 3\ \mu$m) and a ground line ($w_2 = 9\ \mu$m) with a separation length $w_3 = 2\ \mu$m.

[a)]Electronic mail: koji_s@scl.kyoto-u.ac.jp.

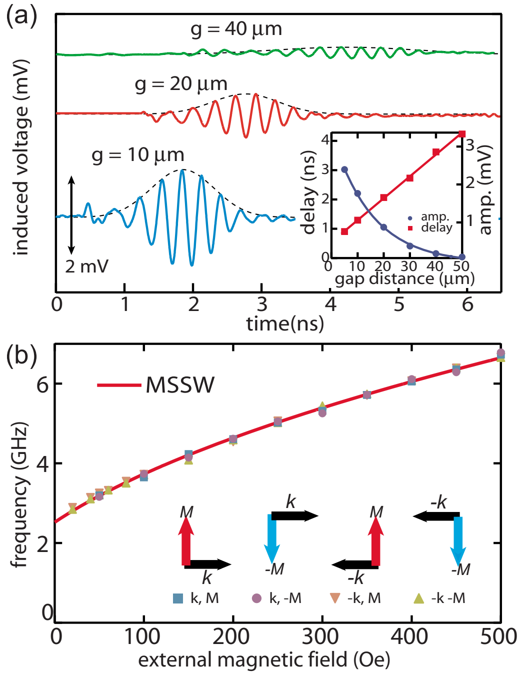

FIG. 2. (Color online) (a) Spin wave signals with different gap distances, exhibiting a propagation of spin wave packet. Inset represents the delay and decay of spin wave packets. (b) Spin wave resonance frequency vs. external magnetic field for four excitation configurations. The data points are obtained by FFT analysis of time domain waveforms.

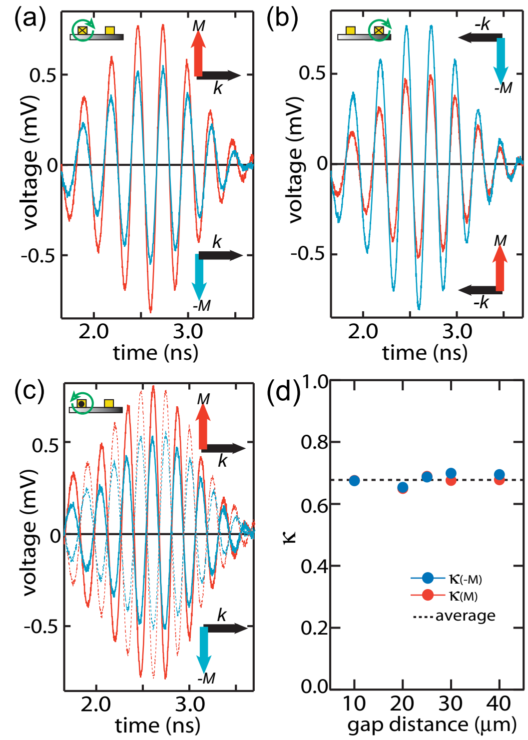

FIG. 3. (Color) Time-resolved waveforms of propagating spin wave ($g=20$ μm) having (a) right moving wavevector k and (b) left moving wavevector $-k$. (c) Waveforms excited by an inversed excitation field $-h_{\text{pulse}}$. The broken lines correspond to the waveforms excited by h_{pulse}, showing phase shifts in π. (d) Nonreciprocal parameter (κ) as a function of gap distance.

$$\omega_{\text{MSSW}}^2/\gamma^2 = \left(H_y + \frac{4\pi M_s}{2}\right)^2 - \left(\frac{4\pi M_s}{2}\right)^2 \exp(-2kd),$$

with the gyromagnetic ratio $\gamma=17.6$ MHz/Oe, the saturation magnetization $4\pi M_s=9650$ Oe, $k=0.5$ μm^{-1}, and the film thickness $d=35$ nm. The magnitude of k agrees with the expected range of $k+\Delta k=0.38\pm 0.3$ μm^{-1} by the ACPS geometry.[9,12] Since $kd\sim 0.018 \ll 1$,[6,12,18] the effect of concentration of Damon–Eshbach mode is negligible.

Figures 3(a) and 3(b) show the waveforms having wave vectors k and $-k$, respectively. As depicted in the Fig. 3(a), the amplitude of propagating spin wave with M, $A_{k,M}$, is larger than that with $-M$, $A_{k,-M}$. Inversely, as shown in Fig. 3(b), the $A_{-k,-M}$ is larger than $A_{-k,M}$. Thus, the amplitude of MSSW signal is governed by the mutual configuration between the magnetization direction and the sign of wave vector, exhibiting nonreciprocity. Furthermore, we observe a distinct π phase shift in MSSW signal by inversing the polarity of excitation voltage as shown in Fig. 3(c), where the waveforms excited by an inverse excitation field are shown by solid lines, while those excited by h_{pulse} are presented by broken lines. This π phase shift corresponds to the reverse of precession direction of spin wave from clockwise to counterclockwise.

To evaluate the nonreciprocity, we define a nonreciprocal parameter (κ) as $\kappa(M)\equiv A_{-k,M}/A_{k,M}$ and $\kappa(-M) \equiv A_{k,-M}/A_{-k,-M}$. In the case of $g=20$ μm, $\kappa(M)=\kappa(-M) =0.65\pm 0.02$. As shown in Fig. 3(d), the parameter κ does not depend on the gap distance, indicating that the origin of nonreciprocity is not the propagation but the excitation process. The nonreciprocal excitation of spin-wave packet can be accounted by considering the pulse magnetic field components of h_z and h_x.[12] In the excitation process, first, the h_x generates a component M_z which produces a demagnetization field H_d normal to the surface. Then the effective field (H_d+h_z) generates a dynamic component M_x, yielding an emission of MSSW packet. Since the direction of h_z in the left side of the excitation strip is opposite to that in the right side, the effective field is asymmetric with respect to the center of the excitation strip, resulting in the asymmetry of the amplitude of spin-wave packet.

The magnitude of κ can be deduced to be $\kappa=0.76$ by the calculation based on the equation reported,[12,18,19] showing 14% difference from the experimentally obtained value. Such a difference between theoretical and experimental nonreciprocity was also reported by recent BLS measurements.[12]

In conclusion, we have shown that we can change the amplitude of spin-wave packet by inversing magnetization direction or by inversing the propagation direction of spin-wave packet. We have also shown that the π phase shift in spin-wave packet is obtained by inversing the excitation pulse field. The difference in amplitude or phase of spin-wave packet can be used as the binary information. Thus our findings lead to the simple method of logical inputs of "1"/"0" into the spin-wave logic circuit.

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