High-order standing spin wave modes in Fe_{19}Ni_{81} micron wire observed by homodyne method

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Abstract. The broadband spin dynamics of patterned ferromagnetic Fe_{19}Ni_{81} microwire with thickness of 80 nm has been investigated experimentally using broadband rectifying method. The rectifying effect provides a highly sensitive method to detect the high-order perpendicular standing spin wave (PSSW) mode. Present analytical calculation reproduces the observed relation between resonance frequency and applied magnetic field. The effective thickness is explained by the pinning condition of magnetic moment at the surface of the wire.

1. Introduction

Spin dynamics in confined structure has been extensively studied by physics and engineering groups [1], since it is significant and important in both fundamental magnetism and device applications. In particular, the excitation of several spin wave modes accompanies non-linear dynamics in mesoscopic magnets whose dimension is comparable to the wavelength and frequency of dipole-exchange spin waves. Such spin dynamics in small magnetic elements has been explored in various ways such as Brillouin light scattering [2], ferromagnetic resonance (FMR) [3, 4], time-resolve magneto optical Kerr effect [5]. In particular, a homodyne method of the microwave propagating in a small magnet provides highly sensitive detection and easy operation for spin dynamics in a small magnet [6 – 13].

The study of quantized and localized spin-wave modes of small magnet is very important because the external radio-frequency (rf) field couples to nonuniform or spin-wave mode of precession in addition to an uniform mode. The contribution to the magnetic energy of these modes arise from a combination of exchange and dipolar interactions.

In this study, we show the relationship between excited spin wave modes and rectifying spectra by comparing the field and frequency dependences of rf current rectification. We discuss them in term of the perpendicular standing spin wave (PSSW) mode. The mode depends on the exchange interaction in the ferromagnet and is quantized due to pinning of the moments at the surface [12 – 15].

2. Experimental procedure

In this study, we detect the high-order PSSW mode using the rectifying effect [12, 13]. A schematic experimental diagram and an optical microscope image of the wire are shown in figure 1(a) and 1(b), respectively. A single layered 80 nm thick Fe_{19}Ni_{81} wire is fabricated onto a polished MgO substrate.
by means of ultra-high vacuum e-beam evaporation, e-beam lithography and lift-off method. The width and length of the wire are 5 \( \mu \)m and 150 \( \mu \)m, respectively. The electrodes made from Cr (5 nm thickness) and Au (85 nm thickness) form a coplanar waveguide structure [8, 13]. The centre conductive strip line is placed on the wire within the coplanar waveguide structure. A sinusoidal continuous wave rf current with power of +10 dBm was injected into the wire by a signal generator. We measure the rectifying voltage of the wire along the long axis.

3. Experimental result and discussion

The magnetic field is applied at angle \( \theta = 45^\circ \) to the longitudinal axis of the wire in plane. Figure 2 shows the frequency dependence of the detected rectifying spectra at the external magnetic fields \( H = 190, 290 \) and \( 390 \) Oe. For clarity, the detected spectra are shown in the rf frequency range between (a) 0 and 15, (b) 15 and 20 and (c) 20 and 30 GHz.

Four resonance frequencies are observed as shown in figure 2. The lowest resonance frequency is derived from the uniform mode. The higher-order PSSW modes of the index \( n = 1, 2, \) and \( 3 \) are also clearly observed. The PSSW mode with the index \( n = 1 \) reconfirmed our previous experimental result [13]. The same behaviour of the PSSW mode was observed in the present study, while the present resonance frequency was not consistent with the previous one because each thickness was different [13].

![Figure 1](image_url)

**Figure 1.** (a) Schematic circuit and experimental setup of the system consisting electrodes and magnetic wire. (b) Optical microscope image (top view).
The detected signal is derived from the time variation of the anisotropic magnetoresistance. As the sample resistance \( R(t) = R_0 + \Delta R \cos^2(\omega t + \phi) \) oscillates in response to the rf excitation current \( I(t) = I_0 \cos(\omega t) \), a rectifying voltage is generated across the wire due to the phase difference \( \phi \) between the current and the resistance, where \( R_0 \) is the resistance independent of the time \( t \) and \( \Delta R \equiv R_\parallel - R_\perp \) is the resistance difference between the magnetizations parallel and perpendicular to the current. The details of the analytical model are presented by ref. 9, 10 and 11. The sign of the rectifying signal is determined by the phase difference \( \phi \) that is derived from the spin wave modulation mode.

The magnetic field dependence of the resonance frequency of the wire is shown in figure 3. The frequency variation in the PSSW mode with applied field is qualitatively understood in a term of the rectangular cross-sectional wire. Accordingly to Kalinikos and Slavin [14], the dispersion relationship of the PSSW in a confined magnetic structure is given by

\[
\omega_n^2 = \gamma^2 \left[ H + \frac{2A}{M_S} \left( \frac{n\pi}{d_{\text{eff}}} \right)^2 \right] \left[ H + \frac{2A}{M_S} \left( \frac{n\pi}{d_{\text{eff}}} \right)^2 \right] + \frac{M_S}{\mu_0},
\]

where \( d_{\text{eff}} \) is the effective thickness for the PSSW mode wavelength including the boundary conditions [12, 14, 15], \( n \) the quantized number for the PSSW along the thickness direction, and \( \mu_0 \) and \( \gamma \) the vacuum permeability and gyromagnetic ratio, respectively.

Figure 3 shows that the experimentally obtained lowest resonance frequency correlates well with calculation of the uniform mode. The comparison between the experimental result and the analytical PSSW eigenfrequency estimated from equation (1) is also shown in figure 3. The result implies that the above analytical relation explains our experimental results very well. Consequently, the effective thickness \( d_{\text{eff}} \) is estimated to be 64 nm of which are smaller than the actual thickness of the wire. This indicates that the surface is oxidized and contributes to the pinning of the magnetic moment [12, 15].

Fitting a mode spectral line shape to a linear combination of symmetric and antisymmetric Lorentzians gives the model full width at half maximum \( \Delta f_n \) (FWHM). The FWHM carries information about the mode damping parameter \( \alpha_n \). The damping parameters of the uniform and higher order PSSW modes are estimated to be \( \alpha_{\text{uniform}} \approx 0.0094 \) and \( \alpha_n = 0.0177 \ (n = 1), 0.0177 \ (n = 2) \) and \( 0.0147 \ (n = 3) \), respectively. Compared to damping of the...
uniform mode, the damping parameters of the PSSW modes are enhanced. However, the damping parameters between the higher order PSSW modes are almost same values. If two-magnon scattering process dominates the system, the damping parameters of the higher order PSSW modes are enhanced compared to damping of the $n = 1$ mode. The increase of damping of the PSSW mode with respect to the uniform mode is attributable to a random magnetic potential induced by the wire edge roughness or magnetization pinning centres. In particular, the surface pinning plays an important role on the enhancement of the damping of the PSSW modes. This is in agreement with Ref. 16 and the effective thickness estimation described the above.

![Figure 3](image)

**Figure 3.** Magnetic field dependence of the resonance frequency observed by the rectifying spectra. The lines show the calculations as Kittel mode and equation (1).

4. Conclusions
In summary, highly sensitive measurements of the rectifying spectra in a micron-scale single-layered Fe$_{70}$Ni$_{30}$ strip were performed as a function of rf frequency and external magnetic field. The method provides an easy operation and highly sensitive detection for higher-order perpendicular standing spin wave modes. The observed characteristic for the resonance frequency and magnetic field is quantitatively reproduced by the analytical calculation. This highly sensitive detection of microscopic spin dynamics via the rectifying effect provides a powerful technique for studying the spin dynamics in a nano- or micron-scale confined magnetic structure.

Acknowledgements
The present study is partly supported by MEXT Grants-in-Aid for Scientific Research in a Priority Area, a JSPS Grant-in-Aid for Scientific Research and the JST PRESTO program.

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