Spin Wave Resonance in Perpendicularly Magnetized Synthetic Antiferromagnets

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We report antiferromagnetic spin wave resonance in perpendicularly magnetized synthetic antiferromagnets consisting of Co/Ni multilayers and a thin Ru spacer layer. Two resonance modes were observed in the finite range of the out-of-plane bias magnetic field, where two magnetic moments separated by the Ru layer were antiferromagnetically aligned. These two modes show an opposite dependence on the bias magnetic field and correspond to right-handed and left-handed polarized spin waves. We also theoretically derive the spin wave dispersion for the perpendicularly magnetized synthetic antiferromagnets on the basis of an equation of motion. Our experimental results show good agreement with the theoretical analysis.

**Key words:** antiferromagnetic spin wave, perpendicularly magnetized synthetic antiferromagnets, polarized spin waves, spin wave resonance, multilayers

1. Introduction

Spin waves are collective excitations of ordered magnetic moments in materials and can be used as information carrier and for processing [1-3]. So far, most spin wave devices have been based on ferromagnetic spin waves, and they mainly use spin wave amplitude [4-7] and phase [8-10] to encode information. Unlike ferromagnetic spin waves, spin waves in colinear antiferromagnets have both right-handed and left-handed polarizations [11-12], as shown in Fig. 1. The polarity of antiferromagnetic spin waves is attracting much attention in the recent research field of magnonics, as a new degree of freedom [13-14], in addition to the amplitude and phase. In the past several decades, magnetic resonances with the two kinds of polarities were observed in uniaxial crystal antiferromagnets such as MnF2 [15] or FeF2 [16]. However, it is difficult to excite or manipulate spin waves in crystal antiferromagnets, because they have high resonance frequency of THz regime due to strong exchange coupling. Recent works have focused on not only crystal antiferromagnets but also ferrimagnets for spin wave polarization experiments. In the previous studies, right- and left-handed spin wave polarizations were directly observed by inelastic neutron scattering in yttrium iron garnet [17] and switching of spin wave polarization was observed across the compensated temperature by Brillouin light scattering in GdFeCo films [18].

In synthetic antiferromagnets (SAFs), two magnetic moments separated by a thin nonmagnetic spacer are antiferromagnetically coupled via interlayer exchange coupling. SAFs show weaker exchange interaction than that in crystal antiferromagnets, hence, resonance frequencies of SAFs are in the range of conventional microwave electronics (several tens of GHz regime). These features of SAFs can allow easier detection and manipulation of the antiferromagnetic spin wave modes. In this study, we experimentally investigate spin wave resonance in perpendicularly magnetized SAFs by spectroscopy using a vector network analyzer.

2. Theoretical Analysis

We begin with a theoretical calculation of spin wave dispersion for interlayer exchange coupled bilayers with perpendicular magnetic anisotropy (PMA). We consider the system including two ferromagnetic layers FM1, FM2 with the same thickness $t$, the same saturation magnetization $M_s$, and different magnetic anisotropy $K_1 \neq K_2$. Spin wave dispersion with wavevector $k$ can be derived from an equation of motion (EOM) including the dynamic dipolar field due to the nonuniform distribution of local magnetic moments of spin waves. The effective field $H_i$ ($i = 1, 2$) acting on the magnetization $m_i$ ($|m_i| = 1$) of the FM $i$ layer is given by

$$H_i = \left\{ H_{ext} + \left( \frac{2K_i}{\mu_0 M_s} - M_s \right) m_i \right\} \mathbf{e}_z - H_{e2} m_j + H_{dip,ij} \left( i, j = 1, 2, i \neq j \right)$$ (1)

These equations are derived from the equation of motion (EOM) including the dynamic dipolar field and the nonuniform distribution of local magnetic moments of spin waves. The effective field $H_i$ acting on the magnetization $m_i$ ($|m_i| = 1$) of the FM $i$ layer is given by
where \( H_E \) represents the exchange field. The precession of a magnetic moment in the FM layer can be expressed by normalized magnetization \( \mathbf{m} = (m_{x1}, m_{y1}, m_{z1}) \). The \( Z \) axis is parallel to the direction of the out-of-plane magnetic field \( H_{\text{ext}} \) and \( X \) axis is parallel to spin wave propagation direction. The last two terms correspond to the self- and mutual-dipolar fields (given in the Appendix A).

The EOM, \( \frac{d \mathbf{m}}{dt} = -\mu_0 \gamma \mathbf{m} \times \mathbf{H} \), can be linearized by assuming small deviation of the magnetization from the static magnetization direction, \( |m_{x1}|, |m_{y1}| \ll 1 \), and the linearized EOM is given by

\[
i\omega \begin{pmatrix} m_{x1} \\ m_{y1} \\ m_{z1} \end{pmatrix} + \mu_0 \gamma \mathbf{H} \begin{pmatrix} m_{x1} \\ m_{y1} \\ m_{z1} \end{pmatrix} = 0 \tag{2}
\]

where \( \gamma \) is the gyromagnetic ratio. The resonance frequencies \( f = \omega/(2\pi) \) are obtained as the eigenvalues of the 4th order matrix \( \mathbf{H} \), whose elements are explicitly given in the Appendix B.

In the case of antiparallel state, \( m_{x2} \approx 1 \) and \( m_{y2} \approx -1 \) (as shown in the inset of Fig.4), the two resonance frequencies are given by

\[
f_1 = \frac{\mu_0 \gamma}{2\pi} \sqrt{H_a - \sqrt{H_b}}, \tag{3}
\]

\[
f_2 = \frac{\mu_0 \gamma}{2\pi} \sqrt{H_a + \sqrt{H_b}}, \tag{4}
\]

\[
H_a = H_{\text{ext}}^2 + H_{\text{ext}}^B + H_kH_a + \frac{H_{k1}^2 + H_{k2}^2}{2} + H_kM_k t + 4, \\
H_b = 4\left( H_{\text{ext}}^B + \frac{H_B^2}{2} (4H_B + H_a) + \left( H_{\text{ext}}^B + \frac{H_B^2}{2} \right) kM_k t \right) + \frac{H_kk^2M_k^2 t^2}{16},
\]

where \( H_a = H_{k1} + H_{k2}, H_B = H_{k1} - H_{k2} \) and the effective magnetic anisotropy field \( H_{k1} = 2k_1/(\mu_0 M_s) - M_s \). For spin waves with \( k \approx 0 \) \( \mu m^{-1} \), the resonance frequencies become simpler forms as below

\[
f_+ = \frac{\mu_0 \gamma}{4\pi} \left( 2H_{\text{ext}} + H_{k1} - H_{k2} \right)
+ \sqrt{(H_{k1} + H_{k2})(4H_{k1} + H_{k1} + H_{k2})}. \tag{5}
\]

\( f_+ \) (\( f_- \)) increases (decreases) linearly with the applied out-of-plane magnetic field. Here, \( f_+ \) (\( f_- \)) is the resonance frequency for right (left)-handed polarization 24-25 shown in Fig. 1.

4. Experimental Procedure and Results

The films were patterned into \( 50 \times 100 \) \( \mu m^2 \) rectangular wires and then 80 nm-thick SiO2 was deposited for electrical isolation. Subsequently, we fabricated coplanar waveguides for spin wave resonance (SWR) as shown in Fig. 3 (a). Coplanar waveguides were designed for excitation of spin waves with \( k = 1.2 \) \( \mu m^{-1} \). Real \( [S_{11}] \) spectra were obtained by spectroscopy using a vector network analyzer at a given out-of-plane magnetic field. Figure 3 (b) shows a contour plot of SWR spectra generated from the obtained Real \( [S_{11}] \) spectra. The applied magnetic field swept from 250 mT to −250 mT with a step of 10 mT. Two resonance modes were observed from 130 mT to −190 mT, where the two magnetic moments were antiferromagnetically aligned. The slight difference of the field range for the antiparallel state between SQUID and SWR measurements can be due to undesirable changes in the properties of the films during the patterning process. The observed two modes cross at −100 mT and are split by the out-of-plane magnetic field.

3. Magnetic Properties for Sample Films

Films of Ta(0.9) / Pt(2.0) / [Co(0.2) / Ni(0.7)]5 / Co(0.2) / Ru(0.5) / [Co(0.2) / Ni(0.7)]5 / Co(0.2) / Ru(3.0) (unit: nm) were deposited using dc magnetron sputtering on thermally oxidized Si substrates. Two ferromagnetic layers consisting of Co/Ni multilayers are separated by a 0.5 nm-thick Ru layer. Figure 2 shows out-of-plane magnetic hysteresis loop obtained by using superconducting quantum interference device magnetometer. Magnetic moments in the two ferromagnetic layers are perpendicular to the film plane and fully compensated under the out-of-plane magnetic field from 160 mT to −190 mT (from −160 mT to 190 mT). From this result, we determined the saturation magnetization \( M_s = 7.0 \times 10^5 \) A/m and the exchange field \( \mu_0 H_E = J/M_s t = 180 \) mT, where the symbol of \( J \) represents the interlayer exchange coupling 260.

![Fig. 2 Magnetic hysteresis loop measured at 300 K under out-of-plane magnetic field.](Image)

![Fig. 3 (a) Optical micrograph of device for investigating of SWR spectra. Bias magnetic field was applied out of plane. (b) Contour plot of Re \([S_{11}]\).](Image)
5. Discussion

In our experimental case, the attenuation length is estimated to be less than 50 nm from the calculation of \( L = \frac{v_g}{2\pi f/\alpha} \) where \( L \) represents the attenuation length, \( v_g = \frac{\partial (2\pi f)}{\partial k} \) represents the group velocity, \( f \) represents the resonance frequency expressed by Eqs. (3) (4) and \( \alpha = 0.024 \) represents the damping constant for CoNi multilayers.\(^{27}\) Our coplanar waveguides shown in Fig. 3 (a) have a distance of 1 \( \mu \)m between signal and ground antennas. These conditions imply that excited spin waves under one antenna decay before they reach the other two antennas, and that spin waves under each antenna can be regarded as localized uniform precession mode. Therefore, we analyzed our experimental data with the resonance frequencies for spin waves with \( k = 0 \) \( \mu \)m\(^{-1}\). We can obtain the average of PMA for two ferromagnetic layers \((K_1 + K_2)/2\), by linear fitting of the experimental data above 140 mT and below –200 mT with Eq. (17) for parallel state (the details are in the Appendix C). On the other hand, we can obtain the difference of PMA \((K_2 - K_1)/2\) by linear fitting of the experimental data from –190 to 130 mT with Eq. (5) for antiparallel state, because the intersection magnetic field of the two antiferromagnetic resonance modes is given by \((H_{k2} - H_{k1})/2\) which represents the difference of the effective magnetic field between the two ferromagnetic layers as predicted in a previous report.\(^{28}\) While our films consist of two ferromagnetic layers with the same structure, the experimental results shown in Fig. 3 (b) suggest that they have different PMA. Our experimental data gives a good agreement with our experimental data shown in Fig. 3 (b). For the case of parallel state, two resonance frequencies \( f_{P_{In}} \) and \( f_{P_{Out}} \) are theoretically derived (Eqs. (17) (18) in the Appendix C), corresponding to in-phase and out-of-phase precession modes. It should be noted that it is difficult to observe the magnetic resonance for the out-of-phase precession mode, because two ferromagnetic layers are almost identical. For the case of antiparallel state, with comparison of the experimental results and the theoretical analysis, our observed two resonance modes showing opposite tendencies with the bias magnetic field. From the theoretical analysis, our films with different PMA, indicating the Pt under layer induces the stronger PMA in the adjacent (lower) ferromagnetic layer.

Figure 4 shows the applied magnetic field dependence of the resonance frequencies obtained from the theoretical spin wave dispersion for \( k = 0 \) \( \mu \)m\(^{-1}\) (Black lines represent parallel state case, while red and blue lines represent antiparallel state case.) with experimentally determined parameters \((\gamma = 1.88 \times 10^{11} \text{ rad/Ts}, M_s = 7.0 \times 10^5 \text{ A/m}, t = 4.7 \text{ nm}, J = 5.9 \times 10^{-14} \text{ J/m}^2, K_1 = 5.4 \times 10^5 \text{ J/m}^3, K_2 = 4.7 \times 10^5 \text{ J/m}^3\)) which gives a good agreement with our experimental data shown in Fig. 3 (b).

6. Conclusion

In summary, we experimentally and theoretically demonstrated spin wave resonance in perpendicularly magnetized SAFs. In the finite range of the applied out-of-plane magnetic field, two resonance modes for antiferromagnetic state were observed, and they correspond to right- and left-handed polarized spin waves. Our findings will give a route to spin wave devices utilizing spin wave polarization, based on SAFs.

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Appendix

A. Self-dipolar field and mutual dipolar field

For interlayer exchange coupled bilayers with PMA, magnetostatic energy per unit area is given by

\[
E = -\sum_{i=1,2} \mu_0 M_s t_i |m_i| \cdot H_{ext} - \sum_{i=1,2} \left( K_i t_i - \frac{H_{ext}}{2} M_s^2 \right) m_{z_i}^2
+ |m_1| \cdot m_2, \tag{6}
\]

where \( H_{ext} = (0, 0, H_{ext}) \), \( Z \) axis is perpendicular to the film plane, \( X \) axis is parallel to the spin wave propagation direction, the first term is Zeeman energy, the second term is demagnetization, the third term is PMA energy and the last term is interlayer exchange energy.

The effective field is given by

\[
\vec{H}_{eff} = \vec{H}_{ext} + \sum_{i=1,2} \mu_0 M_s t_i |m_i| \times \frac{\vec{m}_i \cdot \vec{m}_2}{|m_1|^2} + \sum_{i=1,2} \left( K_i t_i - \frac{H_{ext}}{2} M_s^2 \right) m_{z_i}^2
+ \sum_{i=1,2} |m_1| \cdot m_2.
\]
\[ H_i = -\nabla m \left( \frac{x}{\mu_0 M_s} \right) + H_{\text{dip},ii} + H_{\text{dip},ij}, \quad (i, j = 1, 2, i \neq j) \]

(7)

where \( H_{\text{dip},ii} \) represents the self-dipolar fields and \( H_{\text{dip},ij} \) represents the mutual-dipolar field. \( H_{\text{dip},ii} \) and \( H_{\text{dip},ij} \) can be obtained by using the Green function \( G_{\text{GR}}(Z - Z') \), given by

\[ G_{\text{GR}}(Z - Z') = \begin{pmatrix} -G_p & 0 & iG_q \\ 0 & 0 & 0 \\ iG_q & 0 & G_p - \delta(Z - Z') \end{pmatrix}, \]

(8)

where \( G_p = (k/2)\exp(-k|Z - Z'|) \) and \( G_q = G_p \text{sgn}(Z - Z') \). The self-dipolar fields \( H_{\text{dip},ii} \) can be calculated by

\[ H_{\text{dip},ii} = \frac{M_s}{\tau} \int_{Z_j}^{t + \tau/2} dZ \int_{Z_j}^{t + \tau/2} dZ' G_{\text{GR}}(Z - Z') \delta m(Z - Z'). \]

(9)

The mutual-dipolar field \( H_{\text{dip},ij} \) can be calculated by

\[ H_{\text{dip},ij} = \frac{M_s}{\tau} \int_{Z_j}^{t + \tau/2} dZ \int_{Z_j}^{t + \tau/2} dZ' G_{\text{GR}}(Z - Z') \delta m(Z - Z'), \]

(10)

where \( \delta m(Z - Z') \) represents relative perturbation of a magnetic oscillation at \( Z' \) position against a magnetic moment at \( Z \) position

\[ \delta m(Z - Z') = e^{-ik|Z - Z'|} \left( \begin{array}{c} m_{x}(Z') \\ m_{y}(Z') \\ 0 \end{array} \right). \]

(12)

and \( s \) represents the thickness of a nonmagnetic spacer between two ferromagnetic films.

By assuming \( ks, kt \ll 1 \), we can obtain \( H_{\text{dip},ii} \) given by

\[ H_{\text{dip},ii} = M_s \left( \begin{array}{c} -k^2 m_{x} \\ 0 \\ 0 \end{array} \right), \]

(13)

and we can obtain \( H_{\text{dip},12} \) and \( H_{\text{dip},21} \) given by

\[ H_{\text{dip},12} = M_s \left( \begin{array}{c} -k^2 m_{x} \\ 0 \\ 0 \end{array} \right), \]

(14)

\[ H_{\text{dip},21} = M_s \left( \begin{array}{c} -k^2 m_{x} \\ 0 \\ 0 \end{array} \right), \]

(15)

B. Resonant frequency for antiparallel state

The spin wave resonant frequency is obtained from the EOM, \( \dot{m} = -\mu_0 M_s \times H_i \), linearized by assuming \( |m_{x}|, |m_{y}| \ll 1 \). In the case of antiparallel state, \( m_{y} = \pm 1 \) and \( m_{x} = \mp 1 \), the linearized EOM is explicitly given by

\[ \begin{pmatrix} m_{x} \\ m_{y} \\ m_{z} \end{pmatrix} + \gamma \begin{pmatrix} 0 & H_{12} & H_{14} \\ H_{21} & 0 & H_{23} \\ H_{41} & H_{42} & 0 \end{pmatrix} \begin{pmatrix} m_{x} \\ m_{y} \\ m_{z} \end{pmatrix} = 0. \]

(16)

Here, the components of 4th order matrix of the effective field \( \hat{H} \) are given by

\[ H_{12} = H_{\text{ext}} \pm H_{k1} \pm H_{E}, \quad H_{14} = \pm H_{E}, \]

\[ H_{23} = -H_{\text{ext}} \mp H_{k1} \mp H_{E}, \]

\[ H_{12} = H_{\text{ext}} \mp H_{k2} \mp H_{E}, \quad H_{14} = \pm H_{E} \pm (kM_{T})/2, \]

\[ H_{34} = H_{\text{ext}} \mp H_{k2} \mp H_{E}, \quad H_{41} = \pm H_{E} \mp (kM_{T})/2, \]

\[ H_{43} = -H_{\text{ext}} \pm H_{k2} \mp H_{E} \pm (kM_{T})/2, \]

the resonant frequency \( f = \omega/2\pi \) is eigenvalue of the matrix \( \hat{H} \) : \( \det(\omega I + \mu_0 \gamma \hat{H}) = 0 \), where \( I \) is the 4th order identity matrix. The obtained two resonance frequencies for antiparallel state are already presented in the main text as Eqs. (3) (4).

C. Resonant frequency for parallel state

In the case of parallel state, \( m_{x} \approx \pm 1 \) and \( m_{y} \approx \pm 1 \), the components of 4th order matrix of the effective field \( \hat{H} \) in Eq. (16) are given by

\[ H_{12} = H_{\text{ext}} \mp H_{k1} \mp H_{E}, \quad H_{14} = \pm H_{E} \]

\[ H_{23} = -H_{\text{ext}} \mp H_{k2} \mp H_{E}, \quad H_{34} = H_{\text{ext}} \mp H_{k2} \mp H_{E}, \]

\[ H_{41} = -H_{\text{ext}} \mp H_{k1} \mp H_{E}, \quad H_{43} = H_{\text{ext}} \mp H_{k1} \mp H_{E}. \]

As well as the antiparallel state case, two resonance frequencies can be obtained from the eigenvalues of the Eq. (16) for parallel state case. For \( k = 0 \mu m^{-2} \), the in-phase and out-of-phase resonance frequencies \( f_{P,\text{in}} \) and \( f_{P,\text{out}} \) for the case of \( m_{x} \approx 1 \) and \( m_{y} \approx 1 \), (or \( m_{x} \approx -1 \) and \( m_{y} \approx -1 \)) are given by

\[ f_{P,\text{in}} = \frac{\mu_0 \gamma}{4\pi} \left[ 2|H_{\text{ext}}| - 2H_{E} + H_{k1} + H_{k2} + \frac{4H_{E}^2 + (H_{k1} - H_{k2})^2}{2} \right]. \]

\[ f_{P,\text{out}} = \frac{\mu_0 \gamma}{4\pi} \left[ 2|H_{\text{ext}}| - 2H_{E} + H_{k1} + H_{k2} - \frac{4H_{E}^2 + (H_{k1} - H_{k2})^2}{2} \right]. \]

The intercept of Eq. (17) is expressed by \( H_{E} \) \((H_{k1} + H_{k2}) \) and \( (H_{k1} - H_{k2}) \). The difference of effective magnetic anisotropy field between two ferromagnetic layers \((H_{k1} - H_{k2})\) can be obtained by the intersection magnetic field of two antiferromagnetic resonance modes expressed by Eq. (5). Therefore, we can obtain the sum of effective magnetic anisotropy field \((H_{k1} + H_{k2})\).

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