Identification and manipulation of spin wave polarizations in perpendicularly magnetized synthetic antiferromagnets

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Abstract
Interlayer exchange-coupled synthetic antiferromagnets (SAFs) have the combined advantages of both high frequency of antiferromagnets and easy detection of ferromagnets. Here, magnetic excitations are investigated by theoretical analysis and micromagnetic simulations in SAFs that consist of two identical ferromagnetic layers with perpendicular magnetic anisotropy. Different from the common in-phase acoustic mode and out-of-phase optic mode, linearly or circularly polarized spin wave modes can be excited at zero bias field by using different types of microwave magnetic fields. Once a bias magnetic field is applied along the easy-axis, left-handed (LH) and right-handed (RH) polarization modes are observed, and the resonance frequency of RH (LH) mode of the SAFs increases (decreases) linearly with the increase of bias magnetic fields until a critical spin-flop field is reached, which is in accordance with collinear antiferromagnets with easy-axis anisotropy. These simulation results agree with the theoretical derivation and provide fundamental insight into the nature of dynamic properties of the perpendicularly magnetized SAFs, which may provide new prospects for spintronic applications.

1. Introduction
Exchange interaction induced magnetic excitations, called spin waves or magnons, have attracted great interests for the applications in information processing of spintronic devices [1–7], where the information can be encoded by both the amplitude and the phase of spin waves [8–11]. As a quantum form of spin waves, the magnons are collective spin excitations of magnetically ordered materials such as ferromagnets, ferrimagnets and antiferromagnets. Recent theories [12–14] and experiments [15, 16] reported that magnon excitations at the terahertz (THz) frequency can be generated in crystalline antiferromagnets, characterized by left-handed (LH) and right-handed (RH) polarized spin waves, which have been suggested as a new degree of freedom to encode information or to build spin-torque nano-oscillators with THz ultrahigh frequency signal.

In order to move the antiferromagnets closer to practical applications in the THz spintronic devices, it is essential to study the intrinsic resonance modes. One powerful tool to probe the dynamic magnetic properties of this eigenmodes is the ferromagnetic resonance (FMR) technique or antiferromagnetic resonance (AFMR) technique [17–20]. In general, for a single ferromagnet with perpendicular magnetic anisotropy (PMA), there will be only one resonance mode and its resonance frequency versus external magnetic field (along the easy-axis) satisfies the Kittel’s formula [21]: ω = γ(H₀ + H_{Keff}). Here γ is the gyromagnetic ratio, H₀ is the bias magnetic field, H_{Keff} = H_K - 4πM_s is the effective anisotropy field, H_K is the PMA field and M_s is the saturation magnetization. Note that the resonance frequency ω increases linearly with the bias magnetic field, as illustrated in figure 1(a). Magnetic moments of the ferromagnet at
resonance state precess counterclockwise (CCW) around the effective magnetic field, which corresponds to a so-called RH polarized spin wave. In contrast, the magnetic resonance in a crystalline antiferromagnet with easy-axis anisotropy could have two different eigenmodes due to the existence of two type of sublattices, and their AFMR frequency reads [22]:

\[ \omega_{\pm} = \gamma \left( \sqrt{H_K (H_K + 2H_E)} \pm H_0 \right), \]

where \( \omega_{+} \) refers to the high frequency mode and \( \omega_{-} \) to the low frequency mode. \( H_E \) is the strong super-exchange antiferromagnetic coupling between the sublattice magnetic moments. We can see that the two resonance modes will degenerate at \( H_0 = 0 \). Thanks to the strong \( H_E \sim 10^6 \) Oe, the resonance frequency at \( H_0 = 0 \) can reach THz (>100 GHz) in MnF\(_2\) [16, 23] or Cr\(_2\)O\(_3\) [15], which is much greater than the resonance frequency of ferromagnets (typical in several GHz) [24]. As illustrated in figure 1(b), the frequency of \( \omega_{+} \) increases while the \( \omega_{-} \) decreases linearly with the external bias field. Remarkably, these two resonance modes have opposite polarizations of magnetization precessions, showing that the \( \omega_{+} \) is a RH precession mode while the \( \omega_{-} \) is a LH precession mode. These two polarized spin wave modes can be excited by incident microwave fields with matching polarization through a Martin–Puplett interferometer [16]. Recently, Cheng et al [25, 26] have proposed a theoretical concept showing that the magnons excited by a uniform spin precession (wave vector \( \vec{k} = 0 \)) can act as the information carrier in the THz signal modulation, which works when the magnetic field \( H_0 \) is lower than a critical field (namely, spin-flop (SF) field \( H_{SF} = \sqrt{H_K (2H_E + H_K)} \)) [27]. In spite of the attractive application prospects, the difficulty of magnetization control and detection in crystalline antiferromagnets is lagging far behind what one could expect. Therefore, searching for fundamental and practical solutions to realize the manipulation of higher frequency in spintronic devices is an issue of vital importance for modern technology.

One approach to achieving the above goal is by replacing the crystalline antiferromagnets with a synthetic antiferromagnet (SAF). This is based on the fact that the SAF system can also serve to achieve the magnetic excitations in tens of GHz [28–31]. The typical SAF stack is composed of two ferromagnetic (FM) layers separated by a thin metallic spacer, and the two FM layers are antiferromagnetically coupled via the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction [32, 33]. Generally, this RKKY coupling strength is almost 100 times weaker than the super-exchange coupling in crystalline antiferromagnets, so that the SAF structure allows magnetic alignments to be manipulated more easily [34–36]. In this study, the magnetic dynamics and magnon polarization in the SAF nanopillars with PMA will be studied. We demonstrate analytically and numerically that two opposite circularly polarized spin wave (magnon) modes can be excited in such a perpendicular SAF nanopillar structure. The observed resonance modes are different from the common acoustic and optic modes reported in the SAF with in-plane magnetic anisotropy [37–41]. We further show that the magnon polarization can be manipulated by tuning the phase angle \( \theta \) of the microwave magnetic excitation fields.

2. Theoretical model

We consider a SAF structure of FeCoB \( (d_1 \text{ nm})/\text{Ru/FeCoB} \ (d_2 \text{ nm}) \) patterned in an elliptical nanopillar, as illustrated in figure 2(a). For simplicity, the two FeCoB layers are assumed to be identical with the same...
thickness \((d_1 = d_2)\). The magnetization precessions of the two FMs are governed by the coupled Landau–Lifshitz–Gilbert equations:

\[
\frac{d\mathbf{M}_i}{dt} = -\gamma |\mathbf{M}_i| \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_S} \left( \mathbf{M}_i \times \frac{d\mathbf{M}_i}{dt} \right), \tag{2}
\]

where \(i = 1 \text{ or } 2\), denoting the bottom and top CoFeB, respectively. \(\alpha\) is the Gilbert damping constant. \(\mathbf{H}_{\text{eff}}\) is the effective field, which includes the anisotropy field \(\mathbf{H}_{\text{K}}\), external bias magnetic field \(\mathbf{H}_{\text{b}}\), interlayer coupling field \(\mathbf{H}_{\text{ex}}\), demagnetizing field \(\mathbf{H}_{\text{n}}\), radio-frequency (\(\text{rf}\)) microwave magnetic field \(\mathbf{h}_{\text{rf}}\). Here we would like to point out that both the self- and mutual-dipolar fields between the two FMs \((\mathbf{h}_{\text{dip},i}, \mathbf{h}_{\text{dip},j})\) [42] have been included into the demagnetizing field \(\mathbf{H}_{\text{n}}\) in our simulations. The bias magnetic field is applied along the \(z\)-axis direction, and the microwave field is applied in the film plane: \(\mathbf{h}_{\text{rf}} = \{h_0 \cos(\omega t), h_0 \sin(\omega t), 0\}\). By tuning the phase factor \(\theta\), the \(\text{rf}\) microwave field can rotate around the \(z\)-axis either CCW for \(\theta = 0\) or clockwise (CW) for \(\theta = \pi\).

Theoretically, after neglecting the damping term, equation (2) can be easily solved in its linearized approximation equation by using macrospin model. And then the dispersion relations of the PMA–SAF can be derived analytically. In this case, we consider a uniform precession mode \((\mathbf{k} = 0)\) of the SAF, so that the influence of dynamic dipolar field \(\mathbf{h}_{\text{dip}}\) can be ignored in theoretical models [42–46]. In the small signal approximation, the precessing magnetization vector \(\mathbf{M}_i\) can be separated into two components: the saturation magnetization \(M_{\text{s}}\), and the rf magnetization \(\mathbf{m}\). The total magnetization of each FM \(\mathbf{M}_i\) can be expanded around their own equilibrium positions as \(\mathbf{M}_i = (m_{ix} \mathbf{e}_x + m_{iy} \mathbf{e}_y) e^{i\omega t} + M_{\text{s}} \mathbf{e}_z (i = 1, 2)\), where \(m_{ix}\) and \(m_{iy}\) are the components of microwave magnetization \(\mathbf{m}\). And the effective field that act on each FM sublayer is given by \(\mathbf{H}_{\text{eff}} = -\frac{\partial E_{\text{tot}}}{\partial \mathbf{m}_i}\). Here \(d_i (i = 1, 2)\) is the thickness of FM layer, \(E_{\text{tot}}\) is the total energy per unit area of the coupled SAF system, given by \(E_{\text{tot}} = \sum_{i=1}^{2} d_i \left( -M_{\text{s}} \mathbf{m}_i \cdot \mathbf{H}_{\text{b}} - \frac{1}{2} M_{\text{s}} H_{\text{eff}}(\mathbf{m}_i \cdot \mathbf{e}_z)^2 \right) + J_{\text{ex}} \mathbf{m}_1 \cdot \mathbf{m}_2\). The first term is the Zeeman energy, the second term is the effective anisotropy energy \((H_{\text{eff}} = \frac{K_{\text{eff}}}{M_{\text{s}}^2} - 4\pi M_{\text{s}})\), and the third term is the interlayer exchange coupling energy between the two FMs.

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**Figure 2.** (a) Schematic of FeCoB/Ru/FeCoB based PMA–SAF structure. The external magnetic bias field \(H_{b}\) is applied along the easy-axis and the \(\text{rf}\) microwave field is applied in the film plane. (b) The FMR response signal as a function of driving frequency of microwave fields at \(H_{b} = 0\). The color-coding refers to the resonance amplitude of magnetization response. Only one resonance state occurs at \(f_{\text{res}} = 4.1\) GHz. Time evolutions of magnetization responses for four different forms of microwave driving fields \(h_0\): (c) \(x\)-type, (d) \(y\)-type, (e) CCW-type, and (f) CW-type, respectively. The volume-averaged magnetizations \(\mathbf{m}_i\) (black curve) and \(\mathbf{m}_j\) (red curve); the net magnetization vector \(\mathbf{m} = (\mathbf{m}_1 + \mathbf{m}_2)/2\) (green curve: \(x\)-component \(m_x\), and blue curve: \(y\)-component \(m_y\)). The corresponding trajectory diagrams of magnetization precession modes are also shown in (c)–(f).
(J_{IEC} is the interlayer exchange coupling constant). In the absence of bias magnetic field or the bias field is smaller than the SF field \(H_{SF} = \sqrt{H_{Keff} + H_{ex}} \), the magnetizations of the two FMs will align completely antiparallel. In this case, by taking \( M_i (i = 1, 2) \) and setting \( m_{1+} = m_{1z} \pm im_{1y} \), \( m_{2+} = m_{2z} \pm im_{2y} \), the LLG equations can be re-written as a 4 × 4 matrix equation with the basis of \((m_{1+}, m_{2+}, m_{1-}, m_{2-})\). The matrix equation can be further simplified as:

\[ \omega \begin{bmatrix} m_+ \\ m_- \end{bmatrix} = \gamma \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix} \begin{bmatrix} m_+ \\ m_- \end{bmatrix}, \]

where \( m_+ = (m_{1+}, m_{2+}) \), \( m_- = (m_{1-}, m_{2-}) \). A and B are the 2 × 2 matrix:

\[ A = \begin{bmatrix} H_0 - H_{ex} - H_{Keff} & -H_{ex} \\ H_{ex} & H_0 + H_{ex} + H_{Keff} \end{bmatrix}, \]

\[ B = \begin{bmatrix} -(H_0 - H_{ex} - H_{Keff}) & H_{ex} \\ -H_{ex} & -(H_0 + H_{ex} + H_{Keff}) \end{bmatrix}. \]

By solving for the eigenvalues of coefficient matrix of equations (4a) and (4b), we then can get the resonance frequencies for this PMA–SAF:

\[ \omega_{RL} = \gamma (\sqrt{H_{Keff}(H_{Keff} + 2H_{ex})} \pm H_0), \]

where \( \omega_R \) and \( \omega_L \) represent the resonance frequencies of the RH mode and LH mode, respectively. Note that, equation (5) is similar to equation (1) for the crystalline antiferromagnets, with the anisotropy field \( H_K \) replaced by the effective PMA field \( H_{Keff} \) and the super-exchange antiferromagnetic coupling \( H_{ex} \) replaced by the RKKY interlayer coupling field \( H_{ex} \). Consequently, the relationship between \( m_{1\pm} \) and \( m_{2\pm} \) at the resonance states can also be easily derived. In the RH mode, we have \( m_1 = m_2 = 0 \) (that is, \( m_{1x} = im_{1y} \) and \( m_{2x} = im_{2y} \)), meaning that both \( m_1 \) and \( m_2 \) precess with the CCW rotation around the external bias field. In contrast, for the LH mode, we have \( m_{1+} = m_{2+} = 0 \) and \( m_1 \) and \( m_2 \) precess with the CW rotation. Note that, if the external magnetic field is zero, from equation (5) we have \( \omega_{RL} = \omega_L = \gamma \sqrt{H_{Keff}(H_{Keff} + 2H_{ex})} \), indicating that these two resonance modes (LH mode and RH mode) with opposite polarizations will degenerate. Interestingly, the degenerated state at zero bias field behaves as a new type of resonance mode which is associated to the pumping microwave fields.

In order to check the above theoretical prediction, we have performed a series of micromagnetic simulations using the open source software OOMMF [47]. In this study, we consider two thickness samples: sample-I \((d_1 = d_2 = 1.0 \text{ nm})\) and sample-II \((d_1 = d_2 = 0.5 \text{ nm})\). The lateral dimension of samples is fixed at 100 nm × 50 nm. Typical parameters of CoFeB are taken for the two FM layers [29, 48]: \( M_s = 1000 \text{ emu cm}^{-3} \), \( K = 1.0 \times 10^7 \text{ erg cm}^{-3} \), \( A = 2.0 \times 10^{-6} \text{ erg cm}^{-1} \), \( \alpha = 0.01 \) and \( J_{IEC} = -1.0 \text{ erg cm}^{-2} \). In this case, \( H_{ex} \) is smaller (larger) than \( H_{Keff} \) for sample-I (sample-II), which results in the magnetization hysteresis loop without (with) the intermediate SF state (we will discuss them in figure 3 and figure 5, respectively).

3. Results and discussion

3.1. Dynamic properties for the sample without SF state

We first performed simulations for a PMA–SAF sample with FeCoB (1 nm)/ Ru/FeCoB (1 nm). As predicted by the above theory, only one resonance frequency is observed at \( f_{FMR} = \omega / (2\pi) = 41 \text{ GHz} \) in the absence of bias field, as shown in figure 2(b), revealing that the LH mode and RH mode degenerate completely. This resonance frequency is independent on the type of rf driving magnetic fields \( h_{rf} \), checked by using four forms of microwave fields with a fixed amplitude of \( h_0 = 30 \text{ Oe} \) but different directions. The detailed temporal evolutions of magnetization responses are shown in figures 2(c)–(f), respectively. The first feature we would like to emphasize is that the two FMs resonate at the same frequency of 41 GHz, no matter what kind of microwave driving fields is applied. Secondly, the magnetization precession modes show completely different behavior for the four different types of microwave driving fields. When the x-type microwave magnetic field \( h_{rfx} = h_0 \cos(\omega t)x \) is applied, the x-components \( m_{1x} \) and \( m_{2x} \) oscillate in-phase while the y-components \( m_{1y} \) and \( m_{2y} \) oscillate out-of-phase with time, as shown in figure 2(c). This type of magnetization resonance results in a periodic oscillation in the net magnetization \( \mathbf{m} = (m_{1x} + m_{2x})/2 \) in x-direction \( m_x \) and a constant value in y-direction \( m_y = 0 \). In contrast, for a y-type microwave field \( h_{rfy} = h_0 \cos(\omega t)y \), \( m_{1x} \) and \( m_{2x} \) oscillate out-of-phase while \( m_{1y} \) and \( m_{2y} \) oscillate in-phase, showing an oscillation in \( m_y \) and a constant value in x-direction \( m_x = 0 \).

The value of resonance frequency still remains at \( f_{FMR} = 41 \text{ GHz} \) for the circularly oscillating microwave fields, but both the x- and y-components of the sublayer magnetizations oscillate in the out-of-phase states.
Figure 3. (a) Magnetic hysteresis loop of perpendicular net magnetization versus the perpendicular bias magnetic field for sample-I. The black (red) curve represents forward (backward) sweeping of bias field. The inset shows the corresponding magnetization loop indicated by the Néel vector $\mathbf{I}$. (b) Dispersion relation of frequency with the magnetic bias field. The ball data points and the dash lines represent the simulation and analytical results, respectively. (c) FMR response signal under $H_0 = 2$ kOe. Two obvious resonance states occur at $f_{RH} = 36$ GHz and 47 GHz, respectively. (d) Temporal evolutions of the spatially averaged net magnetization $m_x$ (black curve) and $m_y$ (red curve) precess at different driving frequencies (left panel) and the corresponding frequency spectra calculated by FFT (right panel). The insets illustrate a bird view of magnetization precession around $z$-axis, showing the left-handed polarization mode and RH polarization mode, respectively.

If the microwave field is taken as the CCW form of $h_{rf} = h_0 \cos(\omega t) \hat{x} + h_0 \sin(\omega t) \hat{y}$, the top layer $m_2$ performs an active precession state (large circle) while the bottom layer $m_1$ behaves as a forced precession state (small circle), as shown in figure 2(e). In this case, the two FM layers precess with CCW rotation around the $z$-axis, i.e. RH polarization precession. But if the microwave driving field is taken as the CW form of $h_{rf} = h_0 \cos(\omega t) \hat{x} - h_0 \sin(\omega t) \hat{y}$, $m_1$ will go to the active precession state while $m_2$ will perform as the forced precession state (see figure 2(f)). In this case, the two FM layers have a LH polarization precession. These simulation results are supported by our analytical prediction and consistent with the previous theoretical study [49], and qualitatively agree with the results obtained in crystalline antiferromagnets [26]. Specifically, these features are totally different from the commonly in-phase acoustic mode (AM) and out-of-phase optic mode (OM) observed in SAFs with in-plane anisotropy [50–53].

The dynamic magnetic properties of PMA–SAF will change when a static bias magnetic field is applied. For the convenience of discussion, we follow the definition in crystalline antiferromagnets to introduce a Néel vector $\mathbf{I} = (m_1 - m_2)/2$ into the SAF system. We first simulated the magnetic hysteresis loop represented by the perpendicular net magnetization $m_z$ versus $H_0$, as shown in figure 3(a). With the increase of the bias field, the initial antiparallel alignment of SAF ($m_z = 0$) is switched to a saturated parallel alignment state ($m_z = 1$), where the critical switching field is $H_{sat} = 13.5$ kOe (theoretically, $H_{sat} = 2H_{ex} - H_{Keff}$ = 12.5 kOe). Without going through the intermediate SF state, this sudden change process (namely spin-flip transition) normally occurs in a system whose anisotropy energy is larger than the exchange coupling energy.

Figure 3(b) shows the resonance frequency spectra as a function of $H_0$ (i.e. the dispersion relations), where the microwave driving field is taken as $h_{rf} = h_0 \cos(2\pi f_{MW} t) \hat{x}$. Note that, as long as an external bias magnetic field is applied, the degenerated precession mode is immediately eliminated and replaced by the RH and LH mode. The frequency of RH (LH) branch linearly increases (decreases) with the increase of $H_0$ until reaching the critical point $H_{Sat}$. Figure 3(c) show the resonance states at $H_0 = 2$ kOe, in which the rf driving frequency $f_{MW}$ is swept from 20 to 55 GHz. Two distinct resonance states are observed at $f_{LH} = 36$ GHz (LH mode) and $f_{RH} = 47$ GHz (RH mode), respectively. By taking the parameter values of
Figure 4. FMR response curves of PMA–SAF as a function of the phase factor $\theta$ of microwave fields. Here $H_0 = 2$ kOe, $h_0 = 30$ Oe and $\theta$ varies from 0° to 180°. The resonance signal amplitude of the LH mode increases while that of RH mode decreases with $\theta$ increasing.

$H_0$, $H_{\text{Keff}}$ and $H_{\text{ex}}$ into Equation (5), we theoretically estimate the resonance frequencies of the LH and RH modes are $f_L = (\omega_L/2\pi) = 34.9$ GHz and $f_R = (\omega_R/2\pi) = 46.1$ GHz. A little mismatch between the simulation and analytical results ($f_{\text{LH}} - f_L = 1.1$ GHz and $f_{\text{RH}} - f_R = 0.9$ GHz) mainly comes from the size effect of nanopillar in our simulations. Figure 3(d) shows the averaged net magnetization precession and the corresponding frequency spectra for rf microwave fields with different frequencies. One can see that for the driving frequency lower than $f_{\text{LH}}$ (e.g. $f_{\text{MW}} = 30$ GHz), the magnetization precession amplitude is very small ($\delta m_{x,y} < 0.002$), which means that the magnetizations of the two FMs are slightly away from their own equilibrium position. As $f_{\text{MW}}$ is increasing and approaching $f_{\text{LH}}$, the magnetization precession is obviously enhanced. An intensive precession with a relatively large amplitude ($\delta m_{x,y} \approx 0.025$) is then excited when $f_{\text{MW}}$ is taken as 36 GHz, which corresponds to the first resonance state (LH mode), see figure 3(d). After that, the magnetization precession amplitude decreases again until the second resonance frequency of $f_{\text{RH}} = 47$ GHz is reached, at which the second resonance state (RH mode) is observed. For $f_{\text{MW}}$ higher than $f_{\text{RH}}$, the precession amplitude decreases again and no more resonance states appear in our simulations. From the phase of magnetization precession, we can easily identify that the low frequency resonance mode is the LH polarization mode while the high frequency precession mode is the RH polarization mode.

When the bias field is larger than $H_{\text{Sat}}$, the two FMs are forced to the saturation state with parallel magnetization alignment configuration. Theoretically, there will be two solutions of resonance frequencies in this region. One is the in-phase AM whose frequency is described as [50]:

$$\omega_{\text{AM}} = \gamma (H_0 + H_{\text{Keff}}).$$

The other is the out-of-phase OM with the resonance frequency given by:

$$\omega_{\text{OM}} = \gamma (H_0 + H_{\text{Keff}} - 2H_{\text{ex}}).$$

However, the intensity of the OM resonance mode in fact is zero for the SAF with two identical FMs, so that only the AM resonance signal is observed in our simulations, as shown in figure 3(b).

To further understand the spin wave polarization of these two resonance states, we have performed a series of simulations by using microwave driving fields with difference phases. The FMR response signal are shown in figure 4, in which $H_0$ is fixed at 2 kOe, $h_0$ is fixed at 30 Oe while the phase factor $\theta$ varies from 0° to 180°. We can clearly see that the FMR response signal significantly depends on the phase factor. When $\theta = 0°$ (i.e. the CCW-type microwave field), only the RH mode can be excited at $f = 47$ GHz. With the continuous increase of $\theta$, the LH resonance mode appears at a relatively low frequency of $f = 36$ GHz and
Figure 5. (a) Hysteresis loop of magnetization versus perpendicular magnetic bias field for sample-II, showing three stages during magnetization switching (region-I to region-III). The inset shows the corresponding magnetization loop indicated by the Néel vector \( \mathbf{l} \). (b) Dispersion relation of frequency with the magnitude of magnetic bias field. The open circles and the dash lines represent the simulation and analytical results, respectively. (c) and (d) show a typical FMR response signal in the region-II, at which both the \( x \)- and \( y \)-components resonate in phase, namely the AM.

3.2. Dynamics properties for the sample with SF state

The intermediate SF state will appear in the magnetic hysteresis loop by reducing the thickness of FM layers from 1 nm to 0.5 nm, as shown in figure 5(a). In this case, the interlayer coupling field is doubled according to \( H_{\text{ex}} = \frac{|J_{\text{IEC}}| d_{\text{M}} S}{d} \), so that \( H_{\text{ex}} > H_{\text{Keff}} \). At low magnetic fields (region-I, \( H_0 < H_{\text{SF}} \)), the magnetizations of the two FM layers align antiparallel and both the LH and RH modes can be excited, as same as the results shown in sample-I. When the bias field increases toward the critical field \( H_{\text{SF}} \), the magnetization vectors of the two FMs then depart from the \( z \)-axis (i.e. antiferromagnetic axis) and flop into the film plane with a tilted angle to the bias field (i.e. magnetization flop state of the SAF) [51]. In region-II (\( H_{\text{SF}} < H_0 < H_{\text{sat}} \)), the two magnetization vectors are in a scissor-like state with an included angle \( 2\psi \), where \( \cos \psi = H_0 / (H_{\text{sat}}) \). Figure 5(c) shows a typical resonance state at 68 GHz for the given bias field of \( H_0 = 22 \text{ kOe} \). Theoretically, the resonance frequency in region-II satisfies [50, 54]:

\[
\omega_{\text{AM}} = \gamma \sqrt{\frac{2H_{\text{ex}}(2H_{\text{ex}} + H_{\text{Keff}})H_0^2}{(2H_{\text{ex}} - H_{\text{Keff}})^2} - 2H_{\text{ex}}H_{\text{Keff}}}
\]

\[
\omega_{\text{OM}} = 0,
\]

where \( \omega_{\text{AM}} \) denotes the resonance frequency of the in-phase AM and \( \omega_{\text{OM}} \) denotes the out-of-phase OM. From equation (8), we notice that there is only one resonance state in region-II (\( H_{\text{SF}} < H_0 < H_{\text{sat}} \)). This theoretical prediction is also confirmed by our simulation, as shown in figure 5(c). The time evolution of this well-known AM resonance state indicate that both the \( x \)- and \( y \)-components of \( \mathbf{m}_1 \) and \( \mathbf{m}_2 \) precess synchronously (see figure 5(d)). This behavior is different from that shown in the in-plane magnetized SAF, in which both the AM and OM resonance states co-exist in the SF region [50, 55, 56].

Finally, when the bias field is further increased to exceed the saturation field (region-III, \( H_0 > H_{\text{sat}} \)), the magnetization vectors of the two FMs are both forced to the \( z \)-axis direction by the strong static magnetic field. In this region, the SAF trilayer system behaves as a single FM layer despite the existence of AF coupling, and the observed resonance frequency (AM) can be described by the Kittel’s formula given in
Figure 6. FMR response signal as a function of $H_0$ at a fixed driving frequency of (a) $f_{MW} = 30$ GHz and (b) $f_{MW} = 75$ GHz. The magnetic bias field is swept between $-30$ and $+30$ kOe and the rf field is taken as CCW-type or CW type. An additional significant peak signal (AM) appears at the case of $f_{MW} = 75$ GHz.

equation (6). The theoretical prediction of the OM governed by equation (7) indicates that its resonance intensity goes to zero, being consistent with our simulations. Therefore, the OM resonance in region-III is normally called the hidden mode [50, 57].

In order to further confirm the above explanation, we have calculated the resonance signals by sweeping the magnetic bias field, where both the CCW-type and CW-type microwave driving fields with a fixed driving frequency are employed. The simulation results are summarized in figure 6(a) for a driving frequency of $f_{MW} = 30$ GHz and figure 6(b) for $f_{MW} = 75$ GHz, respectively. Note that, when the driving frequency is fixed at 30 GHz, only two resonance signals are observed no matter the microwave field is CW-type or CCW-type rotation. In this case, the LH mode is significant and the SF resonance is very weak. In contrast, for the driving frequency of $f_{MW} = 75$ GHz, three kinds of resonance signals (RH mode, SF mode and AM) can be observed, in which the intensity of AM is obviously greater than those of the other two modes. This result is also perfectly supported by figure 5(b) if we draw two lines at $f = 30$ GHz and 75 GHz, respectively, which clearly show the existence of two resonances for the former case and three resonances for the latter case.

4. Conclusion

In summary, we demonstrate the resonance modes and the corresponding dispersion relationship in SAF nanopillar structures with PMA. In the absence of magnetic bias field, the two magnetization vectors align
antiparallel and one antiferromagnetic resonance frequency has been observed. The chirality of magnetization precessions at the resonance state strongly depends on the type of microwave driving fields, showing the linearly or circularly polarized FMR mode. Once a bias magnetic field is applied, the PMA–SAF system displays two resonance modes with distinct chirality: the low-frequency mode has LH polarization while the high-frequency mode has the RH polarization. The two mode frequencies vary linearly with the bias magnetic field until the bias magnetic field is larger than the critical SF field. After that, only the in-phase acoustic resonance mode exists. Moreover, we can successfully excite magnons with different polarizations by adjusting the phase factor $\theta$ of the driving microwave fields. These findings provide possibility to design magnonic devices by using the SAF nanostructures.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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