

Angle-dependent resonant dynamics of stripes and skyrmions in Re/Co/Pt multilayers

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The dynamic behavior and stabilization of skyrmions in magnetic multilayers are critical for advancing spintronic and magnonic technologies. In our study, we investigate the static and dynamic properties of [Re/Co(d_{Co})/Pt]₂₀ multilayers with varying Co thicknesses (6–24 Å), showcasing a transition from out-of-plane to in-plane magnetic anisotropy. The magnetization reversal leads to a transformation from labyrinth domains to skyrmion bubbles due to the interfacial Dzyaloshinskii-Moriya interaction (iDMI). Using angle-dependent imaging at remanence, we confirm that skyrmions can be stabilized without an external magnetic field at specific polar angles, with the stabilization angle increasing alongside the Co thickness. Ferromagnetic resonance spectroscopy reveals four distinct resonant modes, including low-frequency (2–18 GHz) and high-frequency (20–35 GHz) modes, depending on the magnetization texture. The frequency range of these modes narrows with decreasing effective anisotropy and the iDMI strength decreases in thicker Co layers in perpendicular configurations. These findings link between material properties and skyrmion dynamics directly and demonstrate the feasibility of tunable resonant modes for magnonic devices. By addressing both static and dynamic aspects, our work advances the development of next-generation spintronic and magnonic applications.

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I. INTRODUCTION

The presence of asymmetrical heavy metal layers adjacent to Co leads to an asymmetric interaction known as the interfacial Dzyaloshinskii-Moriya interaction (iDMI) [1]. Skyrmions are topologically stable chiral quasiparticles that can be visualized in systems with lack of inversion symmetry arising at the interface of ferromagnetic and heavy metal heterostructures, i.e., with iDMI and high spin orbit coupling [2–5]. Skyrmions could be potentially used in magnetic data storage devices such as racetrack memory [6,7] or computational devices such as skyrmion-based shuffle computing [8], probabilistic computing [9], skyrmionic magnetic tunnel junctions

[10], reservoir computing and other [11,12], or skyrmion logic gates [13–15]. These skyrmion logic gates might be used for highly efficient computers, which are more fundamental than conventional computers. A lot of research focuses on the stabilization of skyrmions at room temperature in thin film heterostructures [16] and on the static characterization of skyrmions in thin films [1].

The stabilization of skyrmions in absence of any external magnetic field is important for the data storage technology such as racetrack memory [17]. In this light, it was reported that the skyrmion stabilization at remanence could be achieved by applying magnetic pulses or simultaneously applying a static magnetic field both in in-plane (IP) and out-of-plane (OOP) direction [18]. Salikhov *et al.* demonstrated that reducing the applied tilted static field to zero at a particular angle is sufficient to stabilize bubbles at remanence in Pt/Co/Pt multilayers with high perpendicular magnetic anisotropy (PMA) [19].

Recently, the dynamic nature of skyrmions was investigated by applying GHz frequencies in the presence of a magnetic field. Satywali *et al.* studied the magnetization dynamics in Ir/Fe/Co/Pt heterostructures with a thickness near to the spin re-orientation transition [$K_{\text{eff}} \approx 0$ and quality

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TABLE I. List of the fabricated samples.

Sample name	Sample stack
S1	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (8 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)
S2	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (10 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)
S3	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (12 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)
S4	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (16 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)
S5	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (20 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)
S6	Al ₂ O ₃ (0001)/Pt (30 Å)/[Re (10 Å)/Co (24 Å)/Pt (10 Å)] ₂₀ /Pt (20 Å)

factor $Q = (2K_U/\mu_0 M_s^2) = 1$] confirmed by superconducting quantum interference device (SQUID) magnetometry [20], where K_{eff} is the effective anisotropy, Q is the quality factor, K_U is the uniaxial anisotropy, and M_s is the saturation magnetization. Here, we have defined the effective anisotropy as the area between in-plane and out-of-plane MH loop measured by SQUID magnetometer, $K_{\text{eff}} = K_U - \mu_0 M_s^2/2$. For our convenience we have considered $K_{\text{eff}} < 0$ for the out-of-plane easy-axis samples (Co thickness equal to 8, 10, and 12 Å) and $K_{\text{eff}} > 0$ for the in-plane easy-axis samples (Co thickness equal to 16, 20, and 24 Å). Similarly, the effective magnetization, estimated from the ferromagnetic resonance (FMR) measurements, can be written as $\mu_0 M_{\text{eff}} = \mu_0 M_s - \frac{2K_{2\perp}}{M_s}$, where $2K_{2\perp}$ is uniaxial out-of-plane anisotropy contribution (sometimes called perpendicular magnetic anisotropy, PMA). The value of M_{eff} is negative (positive) for the multilayers with out-of-plane (in-plane) easy axis, respectively [21].

It was observed that there are two distinct modes, a low-frequency (LF) mode and a high-frequency (HF) mode with negative dispersion before the saturation. The LF mode and HF mode are contributed to the counterclockwise (CCW) gyration of the skyrmion cores and the CCW precession modes, respectively. These modes are highly sensitive to the dipolar interaction between the two ferromagnetic layers. Similar observations have been found in Pt/CoFeB/AlOx heterostructures with overall IP easy axis studied by Srivastava *et al.* [22]. This investigation revealed the existence of three distinct resonant modes such as the LF mode, intermediate frequency (IF) modes, and the HF mode. The LF mode was attributed to the uniform precession of the background magnetization between the skyrmion and the uniform precession of the background magnetization on the top surface of the sample. However, the precession of the skyrmion edges in the central part of the sample is responsible for the IF modes [22]. Moreover, the in-phase precession of the reversed magnetization within the skyrmion cores is responsible for the HF mode and its corresponding excitations extend from the bottom up to the top layers [22]. The above-mentioned properties make skyrmions suitable candidates for usage in rf oscillators [23], rf sensors [24], and reconfigurable magnonic crystals for magnonic devices [25]. Theoretical studies [26] reveal the rich variety of skyrmion eigenmodes in presence of a radio frequency, whereas the azimuthal bound states and the breathing modes are observed in bulk crystals with low damping material at low temperatures [27]. There are few reports dedicated to the dynamics of skyrmions and chiral stripes. An important aspect of chiral stripes is that exciting them with GHz

frequencies could be beneficial for magnonic spintronics devices [28,29]. Recently, it has been found that parallel stripes can behave as reconfigurable magnonic devices [30] possessing a higher group velocity of 2.4 km/s as compared to the velocity of skyrmions and the domain wall. However, the presence of iDMI in heterostructures with out-of-plane easy axis in Re/Co/Pt multilayers (i.e., a quality factor $Q > 1$) has not yet been studied by broadband FMR. Also, the transition of resonant modes from a higher frequency range to low-frequency modes by decreasing the effective anisotropy constant was not studied so far.

In this paper, we explore the stabilization of magnetic skyrmions by applying a magnetic field and, further the stabilization of a skyrmion lattice from labyrinth and stripe domains at remanence by applying an inclined field. We measured the corresponding resonant modes by FMR up to 35 GHz with the static magnetic field parallel and perpendicular to the sample surface. Further, we performed micromagnetic simulations to understand the characteristic and localization of modes arising from the skyrmions and chiral stripes.

II. EXPERIMENTAL DETAILS AND NUMERICAL METHODS

We fabricated the Al₂O₃(0001)/Pt(30 Å)/[Re(10 Å)/Co(d_{Co})/Pt(10 Å)]₂₀ multilayers by molecular beam epitaxy at a pressure of 3×10^{-8} mbar. We prepared samples with Co thicknesses d_{Co} of 8 Å, 10 Å, 12 Å, 16 Å, 20 Å, and 24 Å, respectively. The Pt (30 Å) buffer layer was deposited at 750 °C after annealing the Al₂O₃(0001) substrate at 850 °C. The Pt (20 Å) capping layer prevents oxidation. The sample names are given in Table I.

For the micromagnetic simulations, we use our own version of Mumax3 [31], called Amumax [32], which solves the Landau–Lifshitz–Gilbert equation:

$$\frac{dm}{dt} = \frac{\gamma\mu_0}{1+\alpha^2}(m \times H_{\text{eff}} + \alpha m \times (m \times H_{\text{eff}})),$$

where $m = M/M_s$ is the normalized magnetization, H_{eff} is the effective magnetic field acting on the magnetization, γ is the gyromagnetic ratio, μ_0 is the vacuum permeability. The following components were considered in the effective magnetic field H_{eff} : the demagnetizing field H_d , exchange field H_{exch} , uniaxial magnetic anisotropy field H_{anis} and external magnetic field H_{ext} . Thermal effects were neglected. Thus, the effective field is expressed as

$$H_{\text{eff}} = H_d + H_{\text{exch}} + H_{\text{dmi}} + H_{\text{ext}} + H_{\text{anis}} + h_{\text{mf}}.$$

where the last term, h_{mf} is the microwave magnetic field used for SW excitation. The exchange and anisotropy fields are defined as:

$$\begin{aligned} H_{\text{exch}} &= \frac{2A_{\text{ex}}}{\mu_0 M_S} \Delta m, \\ H_{\text{anis}} &= \frac{2K_{u,\text{bulk}}}{\mu_0 M_S} m_z \hat{z}, \\ H_{\text{dmi}} &= \frac{2D}{M_{\text{sat}}} \left(\frac{\partial m_z}{\partial x}, \frac{\partial m_z}{\partial y}, -\frac{\partial m_x}{\partial x} - \frac{\partial m_y}{\partial y} \right) \end{aligned}$$

where A_{ex} is the exchange constant and D is the interfacial DMI constant.

To gain a better insight into the static and dynamic properties of the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ multilayers, we modeled samples S2 and S4 with $d_{\text{Co}} = 10 \text{ \AA}$ and $16 \text{ \AA}$. The simulations were performed for a finite $2 \mu\text{m} \times 2 \mu\text{m}$ film with periodic boundary conditions along the OOP axis with 32 iterations in both negative and positive z directions and full model along the thickness including magnetic and nonmagnetic layers throughout. We simulated the complete 20-layer repetition of the Re/Co/Pt trilayer (with periodic boundary conditions in the film plane) to get the most accurate account of dipolar effects possible, since it is known that the skyrmion core deviates from the usual tubular structure to more complex three-dimensional configurations due to inhomogeneous dipolar fields along the multilayer thickness [33]. We used the following magnetic parameters: $M_s = 1.3374 \text{ MA/m}$ and $K_u = 1.756 \text{ MJ/m}^3$, $A_{\text{ex}} = 20 \text{ pJ/m}$, $\text{iDMI} = 0.003 \text{ J/m}^2$, and $M_s = 1.3374 \text{ MA/m}$ and $K_u = 1.169 \text{ MJ/m}^3$, $A_{\text{ex}} = 25 \text{ pJ/m}$, $\text{iDMI} = 0.00218 \text{ J/m}^2$ for samples S2 and S4, respectively. We used the gyromagnetic ratio as a fitting parameter to simulate the spin wave dynamics yielding $\gamma = 1.3095 \text{ Mrad/Ts}$ reproducing closely the KM mode frequencies [see Figs. 8(a)–8(d)]. For all calculations, we used a supercell size of $2 \mu\text{m} \times 2 \mu\text{m} \times 58 \text{ nm}$, which we discretized into $486 \times 486 \times 58$ cells for sample S2 and $2 \mu\text{m} \times 2 \mu\text{m} \times 72 \text{ nm}$, which we discretized into $486 \times 486 \times 38$ cells for S4. This corresponds to a lateral cell size of $\approx 4.1 \text{ nm}$, which is below the exchange length $l_{\text{ex}} = \sqrt{2A_{\text{ex}}/(\mu_0 M_S^2)} (\approx 4.2\text{--}4.7 \text{ nm}$ for the parameters used), ensuring an adequate micromagnetic discretization of domain walls and skyrmion cores.

The simulated stack consists of 20 ferromagnetic layers, each 10 and 16 $\text{\AA}$ thick for S2 and S4, respectively, with 20 and 16 $\text{\AA}$ nonmagnetic spacers between them. This was like the experimental setup, where the total thickness of nonmagnetic Pt and Re layers separating adjacent ReCoPt layers is 20 $\text{\AA}$. Periodic boundary conditions were applied in the x and y directions within the plane of the film. To simulate the pinning effects and nonuniformity observed in experimental samples, we employed Voronoi tessellation to create 20 nm grains, each with a unique value of perpendicular magnetic anisotropy. The anisotropy values within these grains were assigned based on a normal distribution centered around the nominal value, with a standard deviation of 5%. The relaxation simulations of the hybridized system were performed using a sequence of Amumax built-in relaxation functions in

four steps: minimization (*minimize*), relaxation (*relax*) with Gilbert damping $\alpha = 1.0$ (for Co layers), and default energy threshold values, solving the full LLG equation (simulation run for 1 ns), and energy minimization again. This sequence allowed us to obtain a stable magnetization configuration.

In our simulations of the hysteresis loops—to avoid the overestimation of coercive field during the remagnetization of a uniformly saturated sample—we developed a “spin injection” method. This approach involves creating several dozens of 20 nm random grains (using Voronoi tessellation) with magnetization randomly oriented within the plane during the initial steps of decreasing the magnetic field in the hysteresis loop simulation. This process is repeated until the grains are stabilized (i.e., they do not remagnetize back to the saturated state). In other words, for various initial field values, we artificially generate “nucleation sites” for remagnetization and attempt to relax and maintain them. This procedure is repeated until the remagnetized regions of the simulated structure are “locked in.” We set a threshold for repeating the spin injection at 98% of the total saturation. The application of this algorithm enabled us to relax the partial remagnetization of the system, allowing for a more accurate reproduction of the hysteresis loop during remagnetization along the easy axis (OOP). To further assist nucleation, before the last relaxation procedure, we also run the simulations at $T = 320 \text{ K}$ for 2 ns using a Gilbert damping parameter of $\alpha = 0.1$.

III. DYNAMIC SIMULATIONS

The SW spectral responses in dependence on the external magnetic field directed along the x and y axes were calculated for values from 2 T to 0 T in decrements of 100 mT. For $k \approx 0$ excitations, the eigenfrequencies are (to good approximation) symmetric under field reversal, whereas iDMI primarily manifests via linear-in- k terms (nonreciprocity) in propagating spin waves. To prevent numerical artifacts arising from a super-symmetry of the spins, we tip the external field by 0.0001 degrees from the z axis and 0.0001 in x axis. During the simulations, we first relax the magnetization in the system until we reach the ground state for specific field amplitude and angle. We then excite the SWs with a global microwave magnetic field along the perpendicular to the external magnetic field, uniform in space, with a *sinc* temporal profile, a cutoff frequency of 60 GHz, and a peak amplitude of $5 \times 10^{-3} \text{ T}$. The excitation field is applied for 1 ns, and we sample the magnetization dynamics at intervals of 2.66 ps over a period of 5 ns. To acquire the SW spectrum, we took the space- and time-resolved IP magnetization and applied a Hamming window along the time axis. We then computed the real discrete Fourier transform using the fast Fourier transform (FFT) algorithm along the time axis for each cuboid composing the system.

To generate the mode visualizations, we individually processed each cuboid in the system by calculating the FFT of the x and y components of the magnetization over time. For a selected frequency, the magnitude of the complex number was mapped as color intensity. This process was

TABLE II. Magnetic properties of the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ multilayers derived from SQUID magnetometry: saturation magnetization M_s , demagnetization energy $\mu_0 M_s^2/2$, effective anisotropy K_{eff} , uniaxial anisotropy K_u , effective anisotropy field $\mu_0 H_{K_{\text{eff}}}$, volume anisotropy K_v , surface anisotropy K_s , domain width parallel to the stripes after demagnetization W , calculated effective iDMI strength $D_{\text{eff}, K_{\text{eff}}}$, using the exchange constants $A_{\text{ex}} = 22, 24$, and $28 \frac{\text{pJ}}{\text{m}}$, surface iDMI parameter $D_{s, K_{\text{eff}}}$, and the maximum number of skyrmions $SK_{n,m}$.

Sample	M_s (kA/m)	$\frac{\mu_0 M_s^2}{2}$ (MJ/m ³)	K_{eff} (MJ/m ³)	K_u (MJ/m ³)	$\mu_0 H_{K_{\text{eff}}}$ (T)	K_v (MJ/m ³)	K_s (mJ/m ²)	W_{stripes} (nm)	$D_{\text{eff}, K_{\text{eff}}}$ (mJ/m ²)	D_s (pJ/m)	$SK_{n,m}/\mu\text{m}^2$
S1	1380	1.19	-0.49	1.69	-0.71			86	3.72	2.99	18
S2	1486	1.38	-0.23	1.62	-0.32			84	2.98	2.98	17
S3	1441	1.30	-0.07	1.37	-0.09			85	2.47	2.97	13
S4	1435	1.29	0.15	1.14	0.20	2.2	0.56	91			12
S5	1447	1.31	0.32	0.99	0.45			90			1
S6	1453	1.32	0.41	0.91	0.57			93			8

repeated for each cuboid in the system to create the complete visualization.

IV. STATIC MAGNETIC PROPERTIES

A. Magnetization reversal of Re/Co/Pt multilayers

We measured the saturation magnetization values of the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ multilayers for IP and OOP direction by SQUID magnetometry at room temperature. The values are listed in Table II. We found a slightly higher saturation magnetization M_s compared to the Co bulk value of 1440 kA/m. This might arise from the magnetic proximity effect at each Co/Pt interface adding some parallel magnetic moment to the whole heterostructure [34,35]. The magnetization reversal occurs from negative saturation field to positive and vice versa. At remanence, the total magnetic moment nearly equals zero suggesting that the magnetic moment in upward and downward directions are equal. Consequently, the formation of labyrinth domains occurs at remanence.

Here, we calculate the effective iDMI amplitude D_{eff} using the K_{eff} method described in Ref. [33]. The exchange constant A_{ex} equals 22, 24, and 28 pJ/m for Co thicknesses of 8, 10, and 12 Å, respectively, and is taken from literature [33,36,37]. In the epitaxial samples, A_{ex} is substantial higher than the sputter-grown magnetic thin films with lower thicknesses [33,36,37]. Interestingly, it has been observed that the value of D_{eff} decreases with increasing Co thickness. However, the surface iDMI constant D_s , which is independent of the thickness [38], remains constant throughout all thicknesses of Co as can be seen from Table II.

B. Field dependence of the magnetic domain evolution and observation of skyrmions in Re/Co/Pt multilayers

To observe the influence of the magnetic field on the domain evolution, we took magnetic force microscopy (MFM) images in field dependence for samples S1, S2, and S3 with $K_{\text{eff}} < 0$ (OOP easy axis) as estimated from the M-H-loops. We applied the different magnetic fields by putting the permanent magnet. We performed the MFM imaging by taking the phase mode signal at 100 nm lift after the topography scan. We used low moment PPP-LM-MFMR tips from Nanosensors. For the angle-dependent MFM imaging, we first applied a tilted field to the sample by an external electromagnet and then performed the MFM imaging at remanence. For the field-

dependent MFM in perpendicular field, we used a permanent magnet with field strength 0.12 T. We set the field strength by the distance between sample and permanent magnet. The field of view of all MFM images is $5 \mu\text{m} \times 5 \mu\text{m}$.

We recorded the field-dependent magnetic domains with increasing the magnetic field [39]. Remarkably, we observed that with increasing the magnetic field in the positive direction, the labyrinth domains transform into bubble skyrmions and eventually reach a saturation state for sample S1 as shown in Figs. 1(a)–1(d). Similarly, the transition from labyrinth domains to skyrmions is observed as the magnetic field increases in positive direction, for samples S2 and S3, as shown in Figs. 1(e)–1(h) and 1(i)–1(l), respectively. The skyrmion bubble density increases significantly with decreasing uniaxial anisotropy energy from 1.69 MJ/m³ to 1.37 MJ/m³ and increasing the thickness. At an external applied field of $\mu_0 H = 0.12$ T, three different states, i.e., the spin-polarized state, the skyrmion state, and the skyrmion lattice state, are observed for samples S1, S2, and S3, respectively, as shown in Figs. 1(d), 1(h), and 1(l). The formation of a bubble skyrmion lattice happens due to the balance of uniaxial anisotropy and iDMI energy. From the above discussion, we have concluded that the samples with negative effective anisotropy (OOP easy axis) undergo a field-induced transformation from labyrinth-type domains to skyrmion lattice with

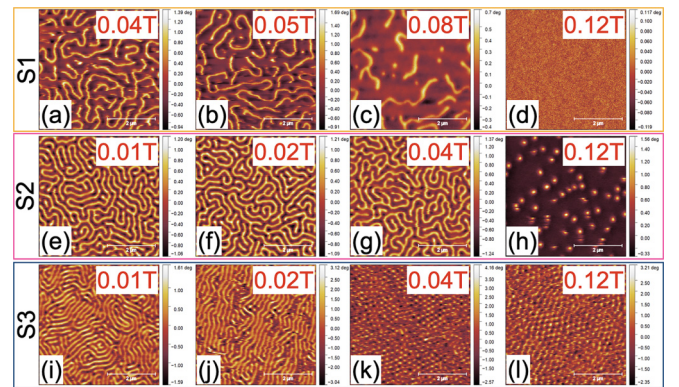


FIG. 1. Evolution of the magnetic domains under an applied field for Co thicknesses of (a)–(d) 8 Å (S1), (e)–(h) 10 Å (S2), and (i)–(l) 12 Å (S3), respectively. All MFM images have the same field-of-view equal to $25 \mu\text{m}^2$.

thickness. This transition reveals a clear relationship between the external-field-dependent skyrmion density and effective anisotropy [40].

C. Stabilization of skyrmions at remanence

In the previous section, we observed that the skyrmions are stabilized by applying the magnetic field normal to the sample. By decreasing the field further to zero, the skyrmion state vanishes and the labyrinth state is restored. In this section, we investigate how to stabilize the magnetic skyrmions at remanence by using the angle-field-dependent MFM method for both IP and OOP easy-axis samples as described in Ref. [19]. Here, we use the following protocol: First, the sample is saturated by applying a DC magnetic field with an amplitude equal to the saturation field in negative direction. After reaching the saturation point, the field gradually is increased to reach the positive saturation point under a particular angle. Again, after reaching the positive saturation point at that particular angle, the field is gradually reduced back to zero. The MFM images are recorded finally at remanence. We repeat this procedure for every desired angle, while keeping the same negative saturation DC magnetic field so that the remanence state should be the same for every angle before applying the positive saturation field. The amplitudes for positive saturation DC field are different for different angles, which have been extrapolated by fitting the straight line from perpendicular saturation field ($\theta_H = 0^\circ$) to IP ($\theta_H = 90^\circ$) saturation field as measured by SQUID. The extrapolated values of the positive saturation field $\mu_0 H_{+DC, \text{Sat}}$ are 1.1 T, 0.85 T, 0.55 T, 0.55 T, 0.65 T, and 0.75 T for samples S1, S2, S3, S4, S5, and S6, respectively.

The various magnetic structures are stabilized when the external positive DC saturation field $\mu_0 H_{+DC, \text{Sat}}$ is applied to the sample at different polar angles θ_H (Fig. 2). When we apply the external field in the IP direction, i.e., $\theta_H = 90^\circ$, the labyrinth domains align in the field direction and become parallel stripes (e.g., sample S1 with 8 Å Co). The perpendicular component of the magnetization increases with decreasing polar angle θ_H of the applied DC field to the sample, breaking the symmetry. The symmetry breaking leads to the transformation of parallel domains into skyrmions because the tilted field provides the additional perpendicular component. Upon reducing the field strength to zero, the energy of the domains is not sufficient to revert them to their original state. Therefore, the competition between perpendicular components and the effective anisotropy field at particular angle plays an important role in the formation of skyrmions.

When we further decrease the angle, the perpendicular component becomes dominant. This leads to the breaking of the parallel stripes [Fig. 2(a)] into individual skyrmions. The skyrmion lattice is formed at $\theta_H = 86^\circ$ as shown in Fig. 2(b). At lower angle, $\theta_H = 82^\circ$, the perpendicular component is dominant even more and, as a result the demagnetization energy is higher in the direction normal to the sample plane. This leads to the transformation of the skyrmions into the labyrinth state with a zig-zag shape. Furthermore, we observe the absence of skyrmions at $\theta_H = 80^\circ$ in Fig. 2(e), while a pure labyrinth state is stabilized at $\theta_H = 0^\circ$ as shown in Fig. 2(f). For other thicknesses of Co, the effective anisotropy K_{eff} increases with the Co thickness becomes positive for sample S4.

The field angle for the stabilization of the skyrmions decreases with increasing effective anisotropy energy with Co thickness. The above described phenomenon occurs for the skyrmion stabilization by tilted field angle for all thickness of Co within a wide range of effective anisotropies. The skyrmion density vs. angle of the applied field is given in Fig. 3.

Here, we have noticed that with increasing the Co thickness, the angle for skyrmion stabilization decreases from $\theta_H = 86^\circ$ to $\theta_H = 0^\circ$ for sample S5 (20 Å Co). We found the highest skyrmion density of 17 skyrmions/ μm^2 for sample S1 as shown in Fig. 3. The green asterisks in Fig. 2 mark the states with maximum number of skyrmions at a particular angle and field. For example, since the samples S2 and S4 exhibit the opposite sign of effective anisotropy strength, the maximum number of skyrmions is stabilized at angles of $\theta_H = 78^\circ$ and $\theta_H = 30^\circ$ for samples S2 and S4, respectively. Furthermore, increasing of the Co thickness stabilizes the maximum number of skyrmions at $\theta_H = 2^\circ$ for sample S6 (24 Å Co).

V. DYNAMIC PROPERTIES

A. Dynamic characterization for IP, OOP, and tilted angles

We performed broadband FMR measurements for field IP and OOP configurations by vector network analyzer FMR using a coplanar waveguide. The DC magnetic field was swept from -2 T to $+2$ T at constant frequencies. We repeated the field sweeps for microwave frequency from $f = 0.5$ GHz to 35 GHz. We take the absolute value of the complex transmission parameter S_{21} as the FMR signal. Figure 4 shows false-color plots of the FMR signal intensity with respect to field strength and frequency. Several resonant modes are observed and analyzed. We observe the spin-polarized uniform mode known as the Kittel resonance mode (denoted by KM in Fig. 4) with positive slope for both IP ($\theta_H = 90^\circ$) and OOP ($\theta_H = 0^\circ$) configurations for all samples after passing the saturation field. Beside these modes, we observe up to three distinct modes in the field range between negative and positive saturation. We attribute them to the dynamics of the magnetic labyrinth domains, parallel domains, and skyrmion states.

For the lowest Co thickness of 8 Å (sample S1), we find the KM starting at higher frequencies around $f = 25$ GHz for the OOP configuration and $f = 15$ GHz for the IP configuration. Additionally, a HF mode is observed above $f = 30$ GHz close to zero field in the OOP configuration, which resembles the resonant modes arising from the presence of both labyrinth domains and skyrmions as depicted in Fig. 4(a). Additionally, three other distinct resonant modes appear, such as the HF mode starting from $f = 27$ GHz, an IF mode appearing between $f = 8$ –27 GHz and a LF mode in between $f = 5$ and 10 GHz for sample S1 in IP configuration as shown in Fig. 4(g). All these modes are due to the excitations of the parallel stripe domains.

When the Co thickness is increased to $d_{\text{Co}} = 10$ Å (sample S2), we observe several changes in the FMR spectra showing that the starting frequency of the KM is shifted toward lower frequencies for both IP and OOP configuration. The KM is accompanied by an additional HF and LF mode. The HF mode exhibits a negative slope in OOP direction. For the IP



FIG. 2. (a)–(f), (g)–(l), (m)–(r), (s)–(x), (y)–(d1), and (e1)–(j1) represent the angle-dependent MFM images for the Co thicknesses of 8 Å, 10 Å, 12 Å, 16 Å, 20 Å, and 24 Å, respectively, at remanence after applying different DC saturation fields under different angles and reduction to zero according to the protocol described in the main text. All MFM images have the same area-of-view equal to $25 \mu\text{m}^2$.

configuration, the KM is accompanied by HF, IF, and LF modes for sample S2 as previously mentioned also for sample S1. However, the starting frequency of the resonant modes is shifted toward lower frequencies. Similarly, in the OOP configuration of sample S3, the Kittel mode is observed along with a HF mode and LF mode like for sample S2. However, the starting frequency for all these modes in S3 is lower as compared to sample S2. The low-frequency modes are observed in nonuniform domain regions (unsaturated magnetic regions) for samples S2 and S3 in OOP configuration. For the IP field configuration, sample S3, in addition to the LF mode and HF mode, exhibits another resonant mode at zero field,

which is constant in field for frequencies up to 20 GHz. It starts from $f = 5$ GHz. We denote it as zero-field-frequency (ZF) mode. A similar type of ZF mode is observed for sample S4 in the IP configuration.

By further increasing the Co thickness from 16 Å to 20 Å and 24 Å (samples S4–S6), the distinct IF mode is clearly observed in the OOP configuration as depicted in Figs. 4(d)–4(f). Alongside the IF mode, the HF and LF modes are also observed, which are associated with the formation of skyrmions and the labyrinth domains as mentioned above. In the spin-polarized state, the KM is observed. With increasing the magnetic field from negative saturation toward

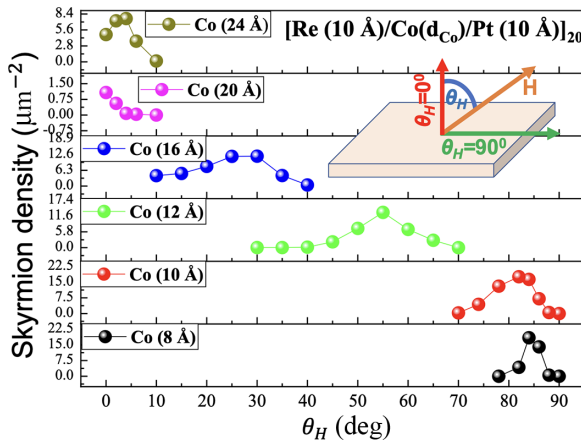


FIG. 3. Dependence of the skyrmion density in remanence on field angle and Co thickness for the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ samples.

positive saturation, the KM mode splits into the LF and IF modes where the IF mode exhibits the negative slope in frequency-field-dependence in the case of samples S4, S5, and S6. Eventually, both IF modes (in positive and negative field regions) approach each other with increasing frequency and merge at a frequency around $f = 18 \text{ GHz}$. Moreover, both IF modes subsequently split into two HF modes, which show the nonsymmetric frequency-field-dependence in nature and display a positive slope in samples S4, S5, and S6, as shown in Figs. 4(d)–4(f).

In comparison to samples S5 and S6 in OOP configuration, sample S4 exhibits a narrow range spread of the HF mode in the frequency spectrum. Notably, in the previous studied multilayers $\text{Ir}/\text{Fe}/\text{Co}/\text{Pt}$ and $\text{Pt}/\text{CoFeB}/\text{AlO}_x$, the presence of the merging IF modes and subsequent splitting to HF modes was not observed [22,39]. The broader spread of the HF modes provides a valuable insight into the existence of skyrmions over a wide range of applied magnetic fields, particularly in the intermediate unsaturated regions between the magnetic saturation points, in the case of samples exhibiting IP anisotropy [39]. For the IP FMR configurations samples S5 and S6 exhibit only the KM as illustrated in Figs. 4(k) and 4(l). To better understand the dynamical behavior at those particular angles where the skyrmions are stabilized at remanence, we performed FMR measurements at additional field angles. The false-color plots of the FMR spectra in Fig. 5 exhibit different distinct excitation patterns compared to the IP and OOP FMR measurements shown before, where the remanent state corresponds to the skyrmion states at these particular angles for both samples S2 and S4. The FMR spectra of S2 [see Figs. 5(a)–5(c)] shows two distinct modes in addition to the Kittel mode.

However, the sample S4 exhibits three distinct modes, including the KM at an angle of 30° . However, it does not show the intermediate frequency mode as compared to the OOP configuration for S4. The HF mode is clearly visible at $\theta_H = 30^\circ$ as compared to $\theta_H = 90^\circ$ (IP), whereas the ZF mode is absent for that particular angle. From the combined analysis of IP, inclined angle and OOP measurements, it is evident that the different resonant modes depend on the Co thickness and

ultimately rely on the anisotropy of the system. Furthermore, the resonant modes of skyrmions, chiral stripes, and labyrinth domains depend upon the magnetic history of the sample. Due to the presence of iDMI, the spin-wave excitation gives the asymmetric nature of resonant frequency. Recently, it has been found that the resonant frequency in the unsaturated states depends upon the direction of the magnetic field [20].

B. Micromagnetic simulations

To corroborate the experimental results, we performed micromagnetic simulations for both statics and dynamics. The field-dependent domain evolution, including the skyrmion formation is simulated by using Amumax [32].

In thin multilayer structures, the ratio of the widths of domains with magnetization oriented downward to those oriented upward is primarily influenced by the Zeeman energy. The size and morphology of these domains are determined by the competition between anisotropy, domain-wall energy, and macroscopic dipolar interactions, while iDMI sets a preferred chirality that can be modified by dipolar fields in thick stacks, leading to hybrid chiral textures and three-dimensional spin structures [33,41,42]. We performed micromagnetic simulations of the field-dependent hysteresis loops using various sets of experimentally measured parameters, and fine-tuning these parameters to achieve the closest match with the experimental observations through a comprehensive 3D numerical model. The simulation results for samples S2 and S4 are presented in Figs. 6(a)–6(d) as solid lines. Our numerical results show strong qualitative agreement with the experimental data, represented by dashed lines. The primary criterion for parameter selection was to accurately reproduce the shape of the hysteresis loop in the perpendicular magnetic field configuration ($\theta_H = 90^\circ$) for S2 and S4 independently. For both samples, the selected parameter sets resulted in IP hysteresis loops with a steeper slope compared to the experimental results. However, the overall magnetization evolution of the samples is accurately reproduced. Notably, for sample S4 in the IP configuration, the shape of the simulated hysteresis loop closely aligns, also particularly demonstrating a strong match in the OOP loop. These findings indicate that the chosen parameters effectively replicate the experimental measurements qualitatively. The observed discrepancies can likely be attributed to the fact that the simulations were conducted at 0 K, thereby neglecting thermal fluctuations, as well as potential differences in effective and surface anisotropies that may be present in the experimental samples but were not accounted for in the model.

In the simulations, during gradually decreasing the amplitude of the external magnetic field, a labyrinth domain pattern emerges at zero magnetic field. As the magnetic field strength increases, these labyrinth domains gradually transform into isolated skyrmions. A noteworthy attribute of the intricate domain and skyrmion configurations is the pronounced variation in their configuration along the thickness of the multilayer (see Supplemental Material Fig. SM-5) [43]. This variation in the core structure is attributed to the fact that the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ multilayers layers are coupled primarily through dipolar interactions. While these interactions are strong enough to ensure the

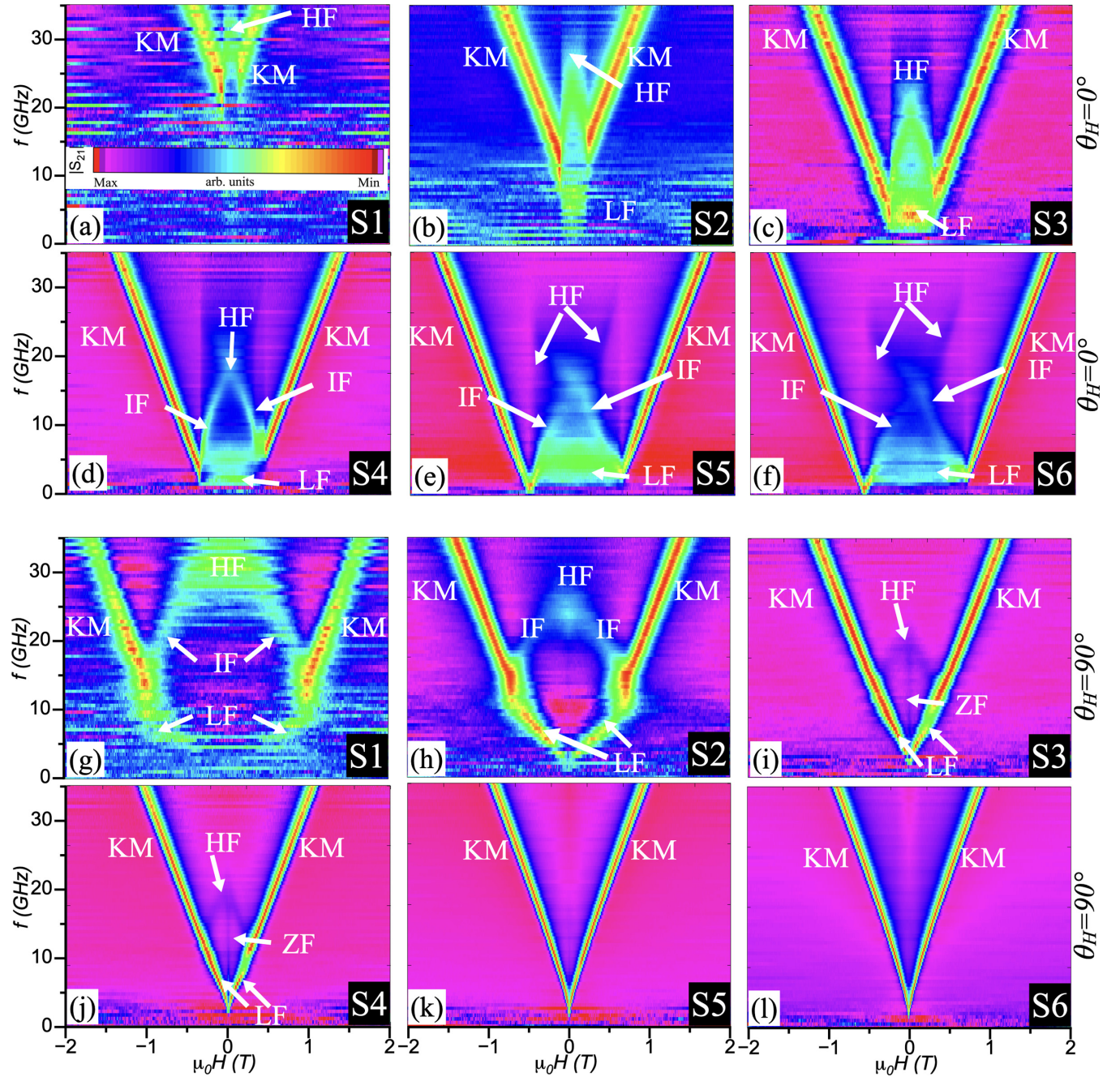


FIG. 4. (a)–(f) Field-frequency-dependence of the FMR signal (color-coded) in out-of-plane configuration ($\theta_H = 0^\circ$) of samples S1 to S6, respectively. (g)–(l) Same for the in-plane configuration ($\theta_H = 90^\circ$).

alignment of the core's centers across the layers, they are insufficient to enforce a coherent magnetization profile, resulting in skyrmion cores and domain structures that are not identical across the thickness. The skyrmions in the bottom half of the stack remain topological ($Q = 1$), while the top half comprises largely nontopological bubbles, with multiple chiral kinks ($Q > 1$). This pronounced three-dimensionality is reminiscent of the “skyrmionic cocoon” states reported for multilayers [41,42].

Figure 7 presents the skyrmion density maps at remanence for samples S2 and S4 as a function of the external magnetic field strength and the field angle relative to the sample plane (θ_H). The simulations commenced with the labyrinthine

domain pattern as initial state, uniformly across all cases. Subsequently, an external magnetic field of specified amplitude and angle (θ_H) was applied. The system was allowed to reach equilibrium under the tilted magnetic field, then the structure was further relaxed into its remanent state. In this remanent state, the number of circular domains (bubbles) were counted and classified as skyrmions. This result demonstrates the influence of both field intensity and direction on the stabilization and density of skyrmions in multilayers. Figure 7(a) shows the skyrmion density map for sample S2. The maximum skyrmion density is observed near the saturation field, as indicated by the dark regions in the color map. The highest number of the skyrmions, 121 in a $4 \mu\text{m}^2$ area (which corresponds to 30

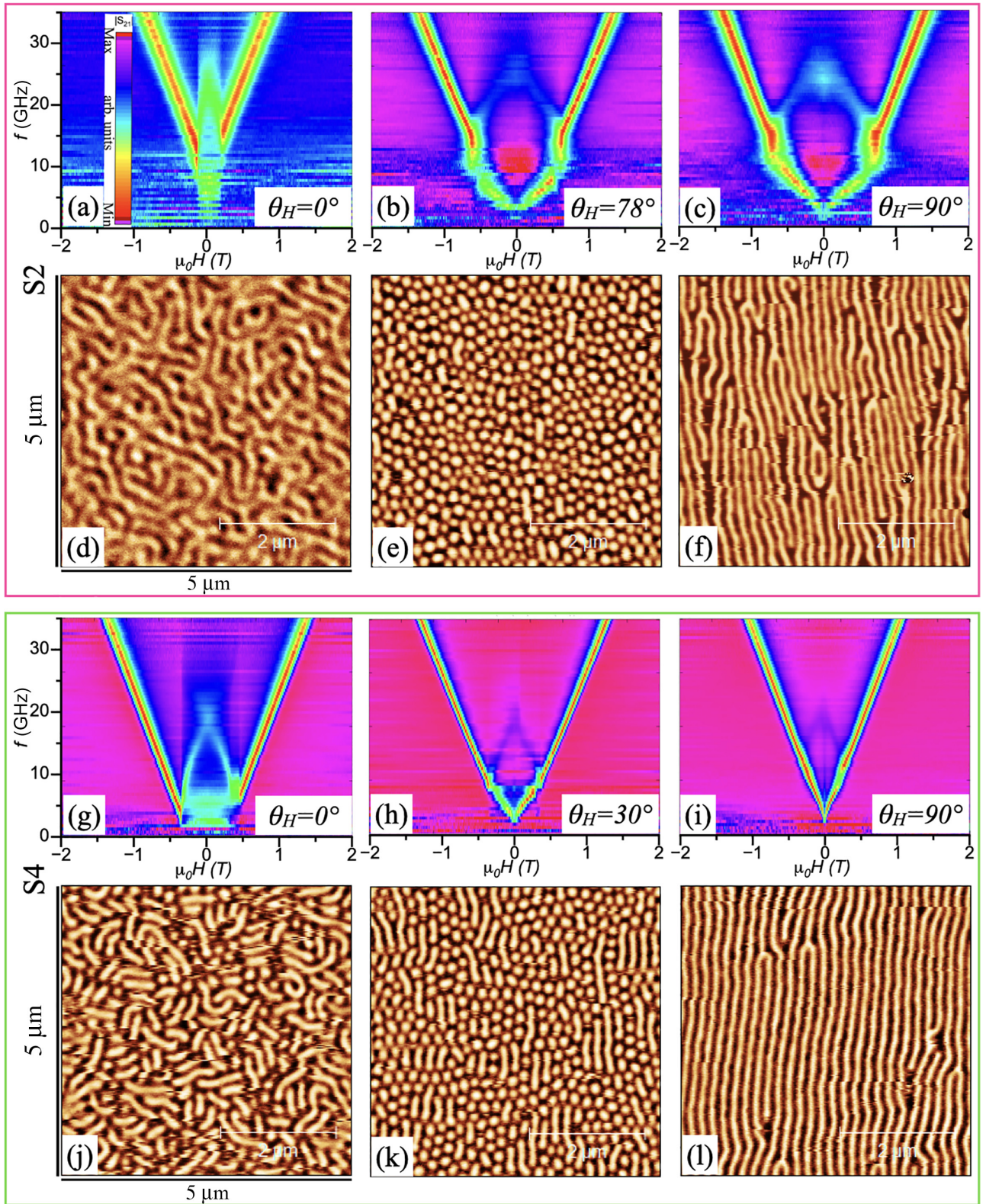


FIG. 5. (a)–(c) False-color plots of the FMR signals of sample S2 vs. field and frequency for angles θ_H of 0° , 78° , and 90° , respectively. (d)–(f) Corresponding MFM images taken at remanence. (g)–(i) FMR spectra at $\theta_H = 0^\circ$, 30° , and 90° for sample S4, which possesses in-plane anisotropy. (j)–(l) Corresponding MFM images at remanence. Note that the FMR spectra of samples S2 and S4 at 0° and 90° are repeated from Fig. 4 for comparison.

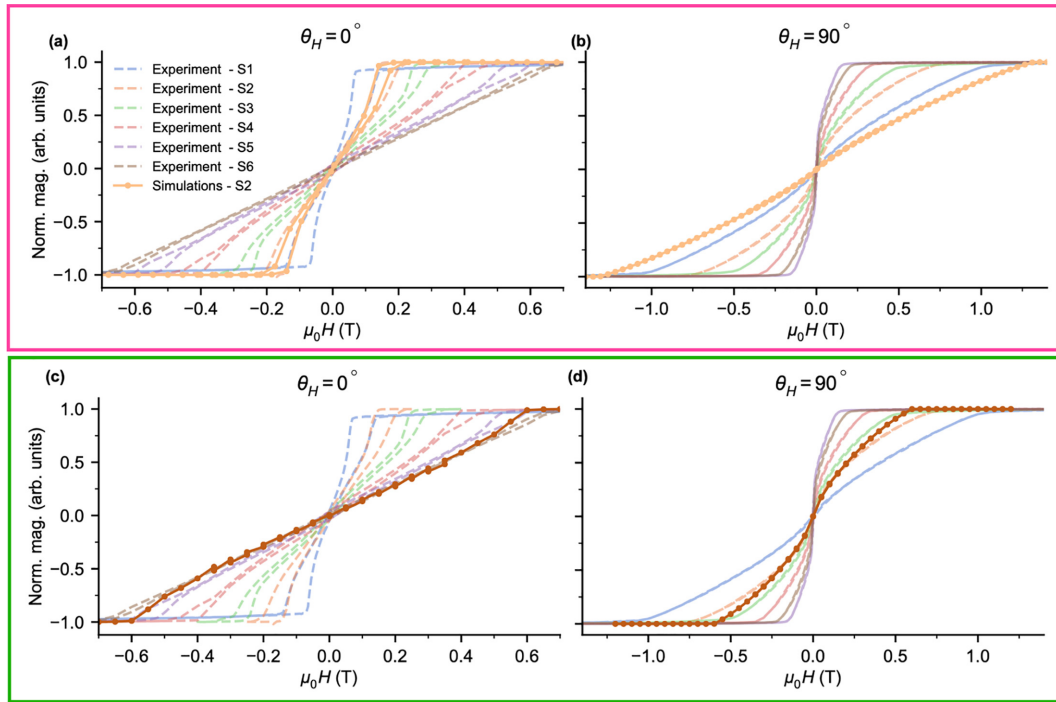


FIG. 6. Hysteresis loops comparing the simulation results and experimental measurements: (a), (b) sample S2 for out-of-plane and in-plane field, respectively. (c), (d) same for sample S4. Each panel shows the normalized magnetization (M/M_S) as a function of the applied magnetic field. The experimental data is represented by dashed lines and the corresponding simulation results are shown by solid lines with circles.

skyrmions per $1 \mu\text{m}^2$), has been observed for an applied field of 1.2 T at an angle of $\theta_H \approx 80^\circ$. These results suggest that a critical factor in the formation of skyrmions in S2 geometries is the high angle of the external magnetic field, approaching almost IP orientation. Figure 7(b) illustrates the skyrmion density for sample S4. In this case, the skyrmion density peaks at lower field strengths compared to S2, reflecting differences in anisotropy and iDMI strength due to the increased Co

thickness. The map reveals a narrower range of field angles where the skyrmions are stabilized. This is consistent with the reduction in effective anisotropy. The highest skyrmion count, namely 94 on a $4 \mu\text{m}^2$ area (equivalent to 24 skyrmions per $1 \mu\text{m}^2$), was observed at 0.45 T and $\theta_H \approx 40^\circ$. These findings indicate that for S4 geometries, the high amplitude of the external magnetic field, approaching the saturation field, is a crucial factor in skyrmion formation. The skyrmion density

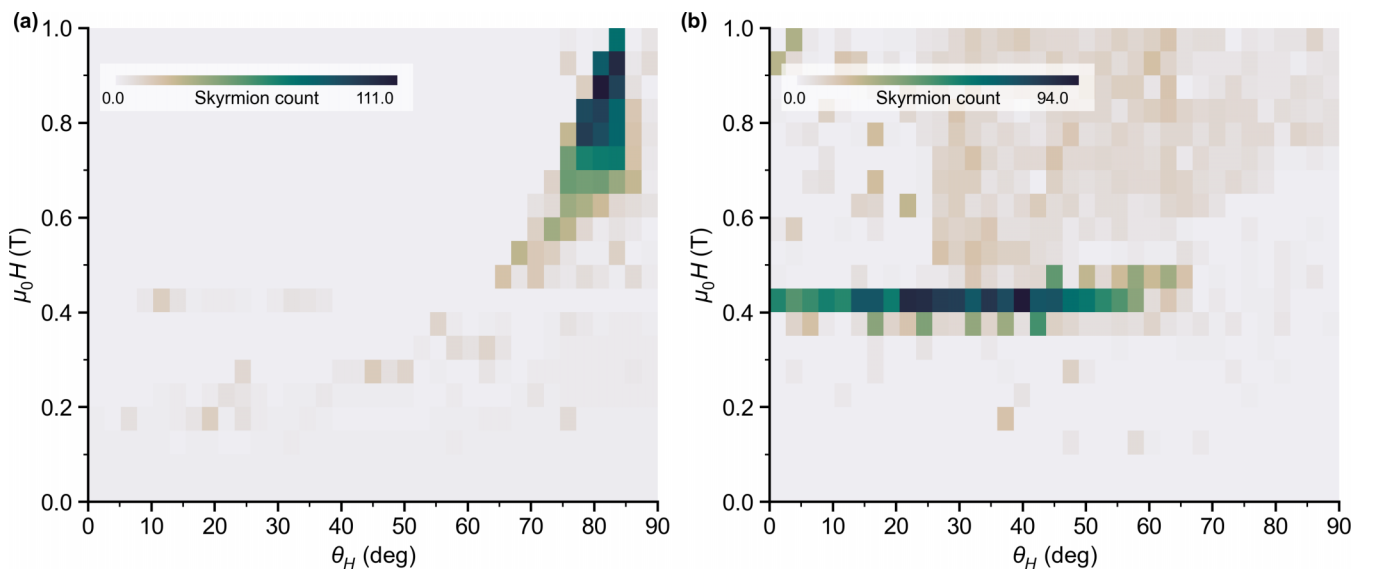


FIG. 7. Simulated skyrmion density at remanence for (a) S2 and (b) S4 as a function of the external-field strength and polar angle θ_H .

slightly deviates from experimental measurements as shown in Table II, which may be attributed to the assumed magnetic parameters and resulting in minor differences in skyrmion size, as well as the method of skyrmion counting and identification. Nonetheless, for the selected material parameters, we achieved strong agreement regarding the magnetic field angle that yields the highest skyrmion density in both S2 and S4 samples. Both maps underscore the critical dependence of skyrmion stability on the interplay between field direction, field strength, and material parameters such as Co thickness and iDMI strength in the skyrmion formation process, the elongation of magnetic domains, driven by the strong magnetic field along the plane of the sample, plays a pivotal role. As the field amplitude approaches the saturation field, the domains become fragmented or vanish. The residual domains that persist randomly in certain layers of the multilayer after the magnetic field is reduced, serve as nucleation sites for skyrmions. Because the remanent fragments originate from quenched disorder, the exact nucleation sites vary between simulation runs; we therefore focus on robust trends (e.g., optimal angles and field ranges) rather than on individual skyrmion positions. To mimic pinning and stochastic nucleation, we applied a Voronoi tessellation generating ~ 20 nm grains with a 5% normal-distribution dispersion in K_U . A dynamic “spin injection” protocol was used during simulated field descent to facilitate natural relaxation and avoid unphysical symmetric pinning.

Next, we discuss the dynamical response of the system, where the FMR is computed under different applied fields, as shown in Figs. 8(a)–8(d) for both the S2 and S4 sample in IP and OOP, respectively. In Fig. 8(a), the evolution of the FMR $f(H)$ -dependence for the S2 sample in OOP field configuration is presented. Two distinct field ranges can be identified, each corresponding to different magnetic texture responses to the external magnetic field excitation. In the first range, corresponding to the skyrmion phase, where the magnetization texture is nonuniform, three distinct types of modes can be observed within the field range of $-0.240 T < \mu_0 H_z < 0.24 T$. Within this range, we identify the low-frequency bulk mode (LF_B) and the high-frequency bulk mode (HF_B), which are presented between 22 and 28 GHz. These modes appear in the experimental measurements for the samples S2 to S6. However, we observe a shift with respect to frequency and field in the simulations. Quantitative frequency offsets between simulations and experiments are expected because the idealized model neglects thermal renormalization of magnetic parameters and does not capture all sources of disorder present in real multilayers.

The amplitude of the LF_B mode is primarily localized in the bulk regions between skyrmions and chiral bubbles. Due to the nonuniform magnetization profile across the thickness of the chiral bubbles, the amplitude of the mode is localized differently within the layers, i.e., concentrated inside the bubbles in some regions, while primarily situated within the bulk for the others. We do not observe a hybridization with the skyrmion modes. Between 2 and 7 GHz, we observe multiple skyrmion resonances. Exemplary, skyrmion gyrotropic and higher-order azimuthal modes with a frequency of 3.9 GHz are present in Fig. 8(e) and labeled as SK_{GA} . The frequencies of these modes vary due to the order of the azimuthal modes

as well as the irregular spatial distribution (mode location) resulting from the varying texture of the domain walls and shape of the skyrmions. The blue dashed line presents a solution of the Kittel formula for the homogeneous mode, including OOP uniaxial anisotropy. Along with the analytical solution in the saturation regime the resonance frequency increases with the applied magnetic field, displaying a typical V-shaped dispersion characteristic for thin films (labeled as KM). Further, applying a perpendicular field (in OOP easy axis) stabilizes a skyrmion-bubble phase. The strong PMA stiffens skyrmion cores and reduces their coupling to a spatially uniform microwave field, consequently, the absorbed power predominantly resides in higher-order azimuthal boundary modes (SK_{GA}) localized along chiral domain walls, as well as bulk-like modes in the interstitial regions. The HF_B mode, as shown in Fig. 8(g), represents a high-frequency excitation chaotically localized around the skyrmion lattice. Its amplitude is distributed irregularly across the IP spatial domain, reflecting its complex and nonuniform character. This lack of localization and irregular spatial distribution results in a lower overall amplitude compared to more coherent modes.

The simulations for the configuration with the external magnetic field applied in the plane of the sample were performed starting from a relaxed labyrinth domain state at remanence, i.e., without skyrmion states [Fig. 8(b)]. Near zero field, we can distinguish a band of modes localized along the domain walls, labeled as $H0_{DE}$ [zero-field domain edge in Fig. 8(b)]. These modes show different degrees of quantization along the domain walls and are observed in the frequency range from 0.5 GHz to 7.5 GHz. The dynamic magnetization landscape of this 7.02 GHz mode is shown in Fig. 8(h) at zero field. These modes have a nearly homogeneous amplitude distribution throughout the thickness. The second branch of modes, called high-frequency domain volume (HF_{DV}) modes is observed both in the domain’s volume and at the domain surface. It exhibits a negative slope, which is associated with the softening of these modes [Figs. 8(b) and 8(j)]. The HF_{DV} mode exhibits an asymmetric precessional amplitude along the multilayer thickness. This asymmetry originates from the three-dimensional magnetostatic boundary conditions of the 20-repeat stack: large stray fields near the surfaces twist domain walls away from ideal Néel character and can create nontopological “skyrmionic cocoons” and chiral kinks [41,42]. The upper layers display a generally higher amplitude than the lower layers—a behavior attributed to the presence of iDMI in the sample and the inhomogeneous magnetic texture through the thickness (see Supplemental Material, Fig. SM-5) [43]. Together with iDMI-imposed chirality, this produces a depth-dependent effective field landscape that can act as a trapping potential for localized modes, leading to enhanced precession amplitudes near one surface and to the observed negative dispersion of selected branches [44].

The last group of modes, labeled as low-frequency domain wall LF_{DV} modes, are localized within the walls of the magnetic domains. These modes form a V-shaped band in the same frequency range as the $H0_{DE}$ modes. Above 1 T, the domain walls disappear, resulting in the vanishing of this band. At higher fields, a uniform mode (KM) is observed. The LF_{DV} modes are not uniform across the plane of the

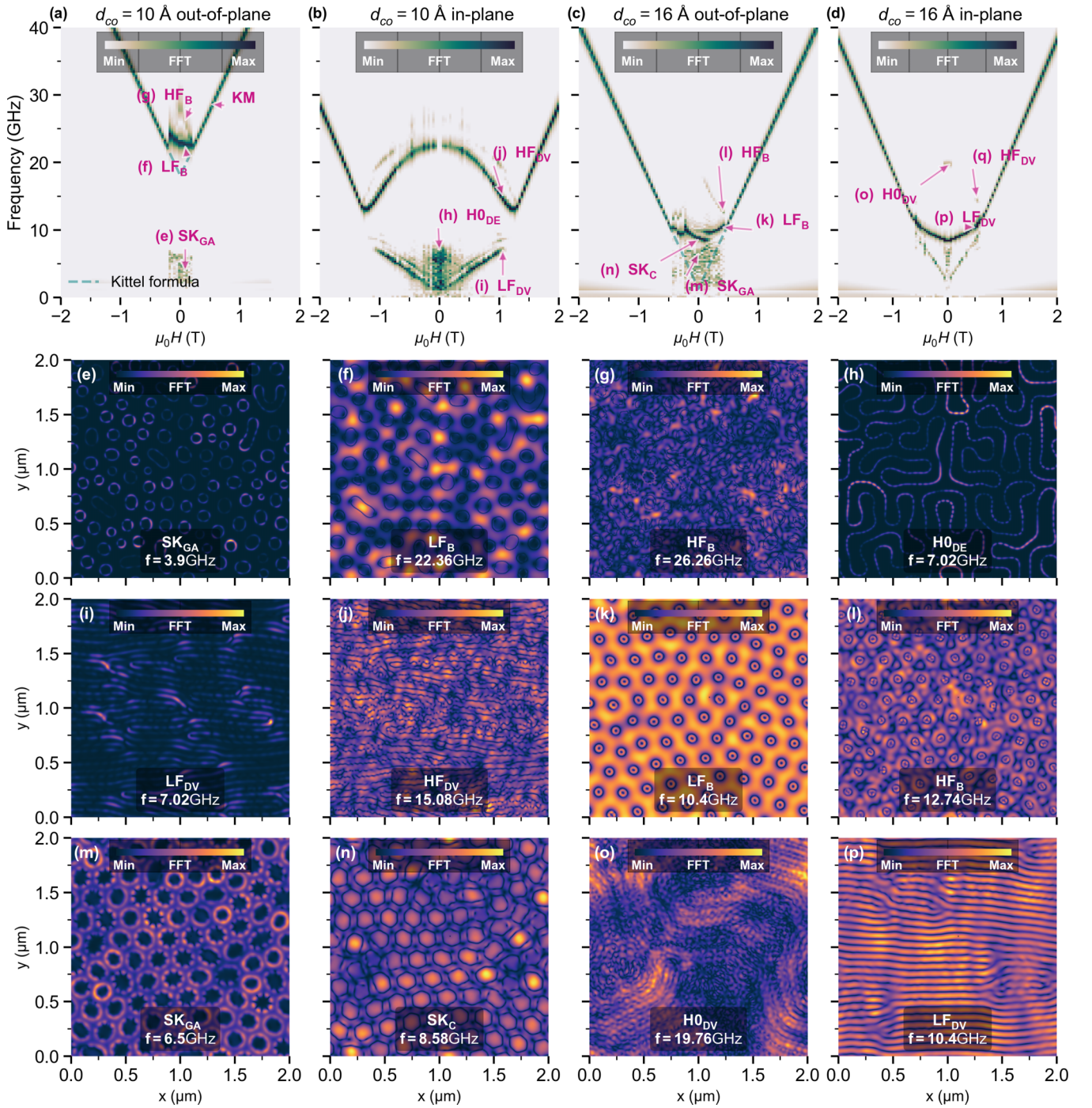


FIG. 8. Simulated FMR field-frequency spectra and corresponding spatial FFT amplitude maps. (a), (b) spectra for S2 under OOP and IP fields; (c), (d) spectra for S4 under OOP and IP fields. Panels (e)–(p) show representative eigenmode profiles, including azimuthal edge resonances (SK_{GA}), domain-edge modes ($H0_{DE}$), and domain-volume modes. Additional mode profiles not shown in panels (e)–(p) due to space limitations (e.g., the HF_{DV} branch labeled (q) in the spectra) are provided in the Supplemental Material SM6 [43]. Magenta markers (markers) in panels (a)–(d) indicate the external fields at which the corresponding FFT maps were computed.

sample. Instead, they exhibit amplitude localization in specific segments of the domain walls that are oriented at an angle to the external magnetic field. Unlike the LF_{DV} modes, the HF_{DV} modes do not display asymmetry or inhomogeneity along the thickness [see Figs. 9(b) and 9(f)]. The mode profile of the 15.08-GHz-mode at $\mu_0 H_z = 0.89$ T is depicted in Fig. 8(j).

Simulations for the sample S4 exhibit a similar field dependence, with a noticeably smaller frequency difference between the bulk and skyrmion modes compared to S2. The first low-frequency volume mode, referred to as (LF_B), is illustrated for a field of -0.37 T and a frequency of 10.4 GHz in Fig. 8(k). This mode is characterized by a high amplitude localized in the bulk around the skyrmion lattice hybridized

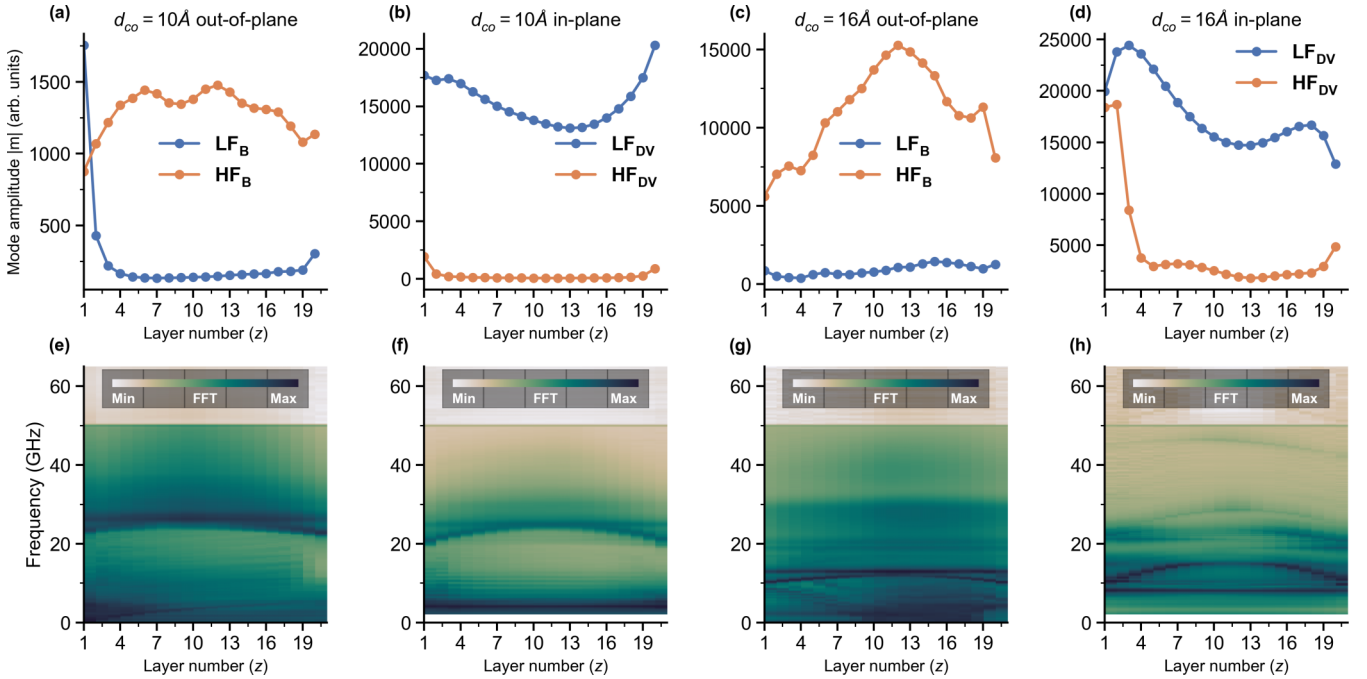


FIG. 9. Layer-resolved mode profiles across the multilayer stack: (a)–(d) Amplitude distribution across the multilayer thickness for selected resonant modes in Fig. 8. The maps are computed at the field points indicated by the magenta markers in Fig. 8. (a)–(d) Corresponding to the sample S2 ($d_{co} = 10 \text{ \AA}$) sample S4 ($d_{co} = 16 \text{ \AA}$). (e)–(h) Frequency distribution through the different layers at a particular applied magnetic field for sample S2 and S4 in both IP and OOP orientations.

with the first-order skyrmion radial mode. It has a uniform profile through the thickness, although the amplitude slightly varies across different layers [see Figs. 9(c) and 9(g)]. This mode displays an almost flat field dependence and is observed in the field range from -0.4 to 0.4 T. Below this mode, we observe a mode called skyrmion edge mode (SK_{GA}) presented in Fig. 8(m) at a frequency of 6.5 GHz and field of -0.368 T. This skyrmion mode is localized in the skyrmion edge, exhibiting an azimuthal character with varying degrees of quantization along the domain wall. This mode also shows a flat field dependence and does not exhibit significant inhomogeneity across the thickness or within the plane of the sample. Below the LF_B mode, in the frequency range above 0.5 to 8.5 GHz, we observed a series of degenerated skyrmion modes with different frequencies and quantization. These modes are nonuniform both in the plane of the sample and along its thickness. An example of such a mode, with a frequency of 8.58 GHz, is presented in Fig. 8(n) at zero field. This mode, observed at zero magnetic field, is a skyrmion mode with amplitude localized in the skyrmion cores (SK_C). These kinds of skyrmion core resonant modes are observed in the frequency range of 7 to 8 GHz in IP easy-axis multilayers of Ir/Fe/Co/Pt [20]. However, Srivastava *et al.* observed this mode in the higher frequency range (12 – 15 GHz) in Ta/CoFeB/AlOx multilayers [22].

Simulations of the S4 system for the IP field configuration reveal a significant reduction in the intensity of the HF_{DV} mode (see Supplemental Material Fig. SM-6) [43]. This mode, observed at a frequency of 15 GHz at remanence, exhibits a negative slope and decreases its frequency to 10 GHz until saturation at approximately 0.6 T. Conversely, the LF_{DV} mode demonstrates two primary branches: one at

higher frequency with relatively flat dependence and another at lower frequency with reduced intensity, resembling a V-shaped dependence typical of the Kittel mode. The profiles of these modes do not differ significantly and represent volume modes with amplitude localized within the domain walls, exhibiting a nonuniform spatial distribution [illustrated in Figs. 8(o) and 8(p) for the $H0_{DV}$ and LF_{DV} modes at frequencies of 19.76 and 10.4 GHz, respectively]. The LF_{DV} mode shows asymmetric amplitude localization with stronger intensity near the lower surface of the sample. In contrast, the HF_{DV} mode also displays pronounced symmetry, with significant amplitude localization at the lower surface. We observe similar tendencies in experiment between S1 and S5, where also decay of HF_{DV} is present. Like in the S2 sample, the LF_{DV} mode is localized within the domain walls in regions perpendicular to the direction of the magnetic field as observed for parallel stripes in LSMO thin films [30]. This mode displays also a nonuniform amplitude distribution across the thickness with the maximum amplitude at both surfaces. For thicker samples with IP anisotropy (S4–S6), OOP sweeps reveal an IF branch with negative dispersion. Micromagnetically, this IF branch is associated with hybridized oscillations of domain edges and domain volumes during field-driven domain compression: as the labyrinth network shrinks, boundary conditions evolve continuously, producing negative slopes before saturation.

VI. DISCUSSION

Recently, in Ir/Fe/Co/Pt films the distinct LF and HF modes were observed in the frequency range of 6 – 12 GHz, where the magnetic thickness was $d_{co} = 10 \text{ \AA}$ and the iDMI value was

about 1.4 mJ/m^2 ($D_S = 1.4 \text{ pJ/m}$) [20]. Conversely, in our Re/Co(10 Å)/Pt system, we have identified that the frequency range for the LF mode is $f = 6\text{--}10 \text{ GHz}$ and $f = 20\text{--}27 \text{ GHz}$ for the HF mode, originating from a similar thickness magnetic material but having a twice larger iDMI of 2.98 mJ/m^2 ($D_S = 2.98 \text{ pJ/m}$). In micromagnetic simulations, we have observed three different modes: SK_{GA} , LF_B , and HF_B for perpendicular field orientation. The LF_B mode is localized in between chiral bubbles and skyrmions. However, Satywali *et al.* observed that the skyrmion core eigenmode is responsible for the origin of the low-frequency mode in the $f = 7\text{--}8 \text{ GHz}$ range [20]. We have not found any skyrmion core resonant modes for sample S2. Further, we have observed other so-called skyrmion resonance modes where the spectral intensity is localized at the edge of the skyrmions. Please note that Ir/Fe/Co/Pt [20] and Re/Co(10 Å)/Pt multilayers exhibit negative and positive values of anisotropy, respectively, and different values of the iDMI strength; hence, the different observed eigenmodes.

Similarly, Srivastava *et al.* investigated the system of Ta/CoFeB (12 Å)/AlOx and reported the observation of different excitation modes such as LF modes ($< 2 \text{ GHz}$), IF modes ($2\text{--}8 \text{ GHz}$) and HF modes ($12\text{--}18 \text{ GHz}$) in the perpendicular orientation, where the CoFeB thickness was 12 Å and the iDMI value was 1.2 mJ/m^2 ($D_S = 1.44 \text{ pJ/m}$) [22]. We estimated the iDMI strength of Re/Co (12 Å)/Pt equal to 2.47 mJ/m^2 ($D_S = 2.97 \text{ pJ/m}$). Here, we find a different behavior of the resonant modes, where the LF mode is in the range of $2\text{--}9 \text{ GHz}$ and the HF mode is in the range of $f = 10\text{--}25 \text{ GHz}$ [see Fig. 4(a)]. From the above discussion on the Re/Co/Pt systems, it is clearly evident that with increasing thickness, the strength of the iDMI decreases. This in turn decreases the start and end frequencies for the HF mode and LF modes in the Re/Co/Pt system. Consequently, by adjusting the iDMI strength, it is feasible to tailor the frequency range for different resonant modes and the frequency range for the excitation modes depending on the different material parameters [20,22]. Recently, Satywali *et al.* have observed that the resonant frequency by skyrmion can be changed by varying the different iDMI strength. With increasing the iDMI strength, resonant frequency value can be increased at particular applied field by keeping anisotropy and dipolar energy constant [20]. In sample S4 (IP easy axis), the reduced effective PMA lowers the core stiffness and enables clear numerical observation of fundamental skyrmion core gyration modes (SK_C) in the $0.5\text{--}8.5 \text{ GHz}$ band, consistent with prior reports on gyrotropic core dynamics [20]. However, the Ta/CoFeB (12 Å)/AlOx system exhibits the skyrmion core resonant modes in a higher frequency range of $12\text{--}15 \text{ GHz}$, called HF modes depends upon the iDMI and anisotropy [22]. At the same time, variations of uniaxial anisotropy alone can shift skyrmion resonant frequencies, emphasizing that both anisotropy and iDMI (together with dipolar interactions) contribute to the mode frequencies [45].

Both Ta/CoFeB (12 Å)/AlOx [22] and Re/Co (16 Å)/Pt systems exhibit IP easy-axis magnetization. However, they differ in terms of thickness, anisotropy and iDMI strength. That's why the skyrmion core resonant modes occur in different frequency ranges in these systems. Here, it is worth noting

that skyrmion resonant modes are observed in Ir/Fe/Co/Pt at the frequency of $7\text{--}8 \text{ GHz}$, which is the LF mode region [20]. This difference in observed skyrmion core resonant modes highlights how material composition and structural factors significantly impact the dynamic behavior of magnetic systems. It is reported that by increasing the Co thickness in the multilayers, the stabilization of a skyrmion lattice is observed at larger field ranges [22] in the perpendicular configuration. As a consequence, the different resonant modes are easily distinguished [see Figs. 4(g)–4(i)]. However, the skyrmions stabilizing in lower thickness Co (8 Å) exhibits a narrow field range for their formation, see Fig. 4(a). Therefore, only HF modes are observed in the higher frequency range of $f = 30\text{--}35 \text{ GHz}$ as shown in Fig. 4(a) and other resonant modes are very weak and difficult to visualize.

Similarly, in the IP configuration, the HF, IM, and LF modes due to labyrinth domains are clearly observed with a higher amplitude for 8 and 10 Å thick Co. Similar modes are observed in the simulated FMR spectra for the S2 sample as shown in Figs. 8(b) and 8(h)–8(j). However, we assigned distinct names to the three resonant modes ($\text{H}_{0\text{DE}}$, LF_{DV} , and HF_{DV}). We observed that, with increasing the thickness of Co to 12 or 16 Å, the LF and IF resonant modes vanish with creation of the ZF modes at zero magnetic field. We also found similar types of modes called zero-field domain edge modes ($\text{H}_{0\text{DE}}$) in the simulated FMR spectra for sample S4 as shown in Figs. 8(d) and 8(o). The LF_{DV} and HF_{DV} modes are localized in the domain wall and volume of domains, respectively, due to presence of antiparallel upward and downward labyrinth chiral domains confirmed by the micromagnetic simulation [see Figs. 9(b) and 9(f)]. As a result, it is possible to calculate the frequency band-gap between the LF_{DV} and HF_{DV} modes at zero field. The group velocity of the magnons can be estimated, as it is directly proportional to the frequency band-gap at zero field. It is worth noting that a higher group velocity at zero field is advantageous for magnon-based spintronic devices [28]. For the IP configuration, one can describe the vanishing of the resonant modes due to the labyrinth domains by the magnetostatic interaction and iDMI strength for higher thicknesses of Co, i.e., 20 and 24 Å. Here it is to be noted that the iDMI strength decreases with increasing thickness. Also, the interlayer coupling can affect the resonant modes of parallel stripes. Furthermore, the resonant frequency modes due to labyrinth domains vanish for 20 Å and 24 Å Co.

Further, we determined the anisotropy and effective magnetization by using the resonance equations for a tetragonally distorted cubic (001) system, i.e., distinguishing between IP and OOP anisotropy contributions. The values are listed in Table III. The effective magnetization ($\mu_0 M_{\text{eff}} = \mu_0 M_S - \frac{2K_{21}}{M_{S2}}$) [21,46] is negative for Co thicknesses of 8 Å and 10 Å, which means out-of-plane easy axis. The $\mu_0 M_{\text{eff}}$ is positive for higher Co thicknesses of 16 Å, 20 Å, and 24 Å, which confirms the IP easy axis of magnetization. The 12 Å Co sample is at the spin reorientation transition. FMR and SQUID show opposing results regarding the easy axis. However, the polar angular dependence measured by FMR reveals the truth, namely that the easy-axis direction is tilted to 70° and not 90° [see Supplemental Material Figs. SM-3(c) and SM-3(g)] [43]. Here, it should be noted that we have considered $M_{\text{eff}} < 0$ and

TABLE III. Magnetic parameters of the $[\text{Re}(10 \text{ \AA})/\text{Co}(d_{\text{Co}})/\text{Pt}(10 \text{ \AA})]_{20}$ multilayers extracted from the FMR measurements.

Sample	$\mu_0 M_{\text{eff}}$ (T)	K_U (kJ/m ³)	$\frac{K_{2\perp}}{M_S}$ (mT)	g
S1	-0.764	1724	-12	2.08
S2	-0.395	1682	-28	2.06
S3	0.012	1295	-16	2.15
S4	0.168	1172	-44	2.2
S5	0.467	977	-21	2.19
S6	0.556	922	-6	2.17

$M_{\text{eff}} > 0$ for OOP and IP easy axis (for FMR measurements), respectively, for our convenience.

VII. SUMMARY

We studied the static and dynamic properties of thin epitaxial Re/Co/Pt systems. During the magnetization reversal, we observed the transition from labyrinth domains to skyrmions by field-dependent MFM. This transition is mainly influenced by the Co thickness and eventually the effective anisotropy. Specifically, with increasing Co thickness and decreasing effective anisotropy, we noticed a shift from isolated skyrmions to a skyrmion lattice in perpendicular configuration ($\theta_H = 0^\circ$). Furthermore, we investigate the stabilization of a skyrmion lattice at remanence by applying a static field under an inclined angle. Our findings demonstrate the tunability of the skyrmion density depending on both the effective anisotropy as well as the iDMI strength. By performing angle-dependent measurements, we observed that the stabilization angle for a maximum skyrmion density shift toward lower angles. In dynamical characterization, we revealed the occurrence of different distinct resonant modes corresponding to skyrmion states and parallel stripe domain states from FMR measurements. The observed frequency range of the different resonant modes narrows as the iDMI strength decreases, i.e., with increasing Co thickness. Additionally, we observed that the thicker Co layers show more resonant modes in OOP configuration, whereas the thinner Co layers exhibit a higher number of resonant modes in IP configuration. Furthermore, from angle-dependent FMR measurements at $\theta_H = 78^\circ$ and 30° for samples S2 and S4, respectively, we confirmed that the frequency range of resonant modes lies between those

observed in the IP and OOP configurations. The micromagnetic simulations support our finding. We could identify the different skyrmion-resonant modes such as SK_C , SK_{GA} , and bulk resonant modes such as LF_B and HF_B in OOP orientation. Additionally, we observed a zero-field domain-edge resonant mode H0_{DE} and volume resonant modes such as LF_{DV} , and HF_{DV} due to chiral stripes in IP orientation. The SK_C and SK_{GA} modes are prominent in Co (16 Å), while only the SK_{GA} is observed in Co (8 Å), highlighting their dependence on the Co thickness, anisotropy, and iDMI strength. The formation of chiral stripes by applying an IP field exhibits the different eigenmodes and zero-field frequency bandgap, which could be useful for magnonic devices because of their higher group velocity. Our investigations on the dynamics of epitaxial samples with significantly enhanced iDMI strength hold a great potential for future spintronic devices. The tunability of the resonant frequency through iDMI opens up new exciting possibilities to design and develop GHz frequency-based electronics.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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