

Unconventional magnon-mediated spin torque enabled by ferroelectric domain engineering in multiferroic BiFeO₃

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Yuhan Liang^{1,2,7}, Xingyu Yan^{3,7}, Xiaoyu Jiang^{3,7}, Dingsong Jiang¹, Hao Bai⁴, Zi-An Wang⁵, Hetian Chen³, Xiaofu Qiu³, Daniel Pharis², Xiaoxi Huang², Rakshit Jain^{2,6}, Dingfu Shao⁵, Wanjun Jiang⁴, Di Yi³✉, Daniel C. Ralph^{2,6}✉ & Tianxiang Nan¹✉

Spin current provides an energy-efficient approach for manipulating magnetization, when its spin polarization aligns with the magnetization direction. However, conventional spin-source materials possess high crystalline symmetry, restricting spin polarization to be orthogonal to both spin and charge current directions. Here, we overcome this limitation by utilizing the concept of magnon-mediated spin-orbit torque through integration of the insulating multiferroic BiFeO₃ with a conventional spin-source material. We observe that spin polarization generated by conventional spin-source material can excite unconventional magnon polarization due to the interplay between cycloidal antiferromagnetic order and the ferroelectric domain structure in BiFeO₃. This produces an unconventional magnon torque that allows deterministic, field-free switching of in-plane magnetization collinear with the current direction, unattainable with conventional spin-source materials. Our results establish multiferroic-based heterostructure as a symmetry-engineered magnon spin source, paving the way for low-power spintronic devices.

Spin currents, flows of spin angular momentum characterized by their spin polarization (σ) enable efficient manipulation of magnetization via spin-orbit torques¹, crucial for developing emerging magnetic logic and memory devices^{2–6}. Electron-mediated spin currents can be induced by the spin Hall effect^{7,8} (SHE) or Rashba-Edelstein effect⁹ (REE) in spin-source materials. Nevertheless, the most commonly used spin-source materials, such as polycrystalline heavy metals¹⁰, exhibit high crystalline symmetry, constraining spin polarization σ to be orthogonal to both the charge and spin current directions. Specifically, when a charge current (J_c) flowing along the x -axis generates a spin current (J_m) propagating along the z -axis, the spin polarization is confined strictly to the y -axis, producing only a conventional damping-

like spin torque $\tau_{DL}^y \propto \mathbf{M} \times (\mathbf{y} \times \mathbf{M})$ (Fig. 1a). As a result, efficient field-free magnetization switching is limited exclusively to the y -axis¹¹. Achieving efficient field-free switching along other axes, which is desirable for low-power, high-density magnetic devices, requires unconventional spin polarization (with σ deviating from the y -axis)². Such unconventional spin polarizations have been observed in spin-source materials with reduced crystalline symmetry (Fig. 1b)^{12–16}, or materials with non-collinear antiferromagnetic^{17–21} or altermagnetic orders^{22–24}.

Alternatively, spin angular momentum can be carried by magnons, the collective excitations of magnetic orders, which efficiently propagate magnon currents (J_m) through magnetically-ordered

¹School of Integrated Circuits and Beijing National Research Center for Information Science and Technology (BNRist), Tsinghua University, Beijing 100084, China. ²Department of Physics, Cornell University, Ithaca, New York 14853, USA. ³School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China. ⁴Department of Physics, Tsinghua University, Beijing 100084, China. ⁵Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences, Hefei 230031, China. ⁶Kavli Institute at Cornell, Ithaca, New York 14853, USA. ⁷These authors contributed equally: Yuhan Liang, Xingyu Yan, Xiaoyu Jiang. ✉e-mail: diyi@mail.tsinghua.edu.cn; dcrl4@cornell.edu; nantianxiang@mail.tsinghua.edu.cn

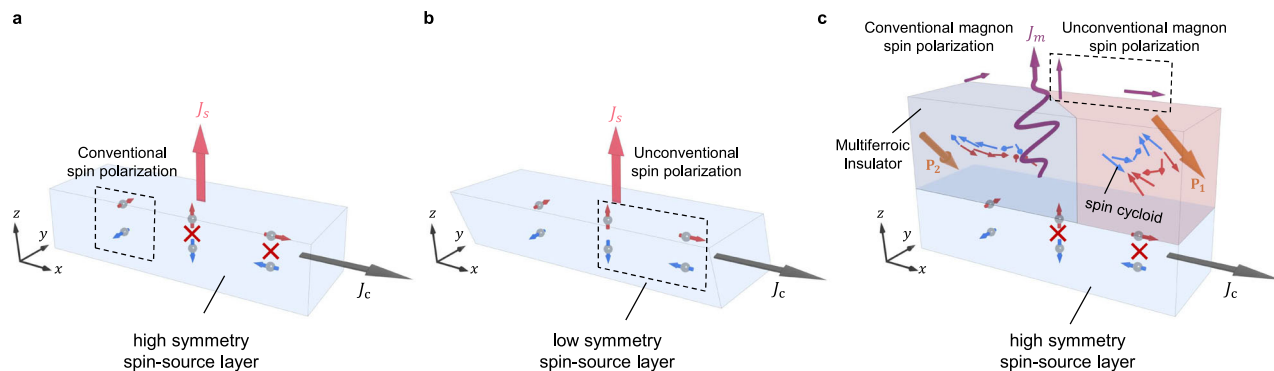


Fig. 1 | Mechanism for the generation of unconventional spin polarization. **a** In a high-symmetry spin-source layer, a charge current J_c applied along the x -direction can induce a vertically flowing spin current J_s with spin polarization σ_y . Unconventional spin polarization components σ_x or σ_z are prohibited by symmetry, as indicated by red cross symbols. **b** In a low-symmetry spin-source layer, a charge current along the x -direction can induce a vertically-flowing J_s with both σ_y and unconventional spin polarization components, as noted by the dashed box. **c** In heterostructures combining a high-symmetry spin-source layer and a multiferroic

insulator with two variant domain structure that possesses ferroelectric polarization ($\mathbf{P}_1$ in domain 1 and $\mathbf{P}_2$ in domain 2) with coupled spin cycloid structure, the spin current can be converted into a magnon current J_m in multiferroic insulator. Due to the low symmetry of multiferroic layers, unconventional spin polarization components σ_x or σ_z can be generated, as noted by the dashed box. Gray spheres represent electrons, while red and blue arrows within them represent the spin polarization σ . The purple arrows represent the magnon spin polarization components.

insulators over long distances without involving charge transport^{25–32}. In heterostructures of spin-source/antiferromagnetic-insulator/ferromagnet, spin currents from a spin-source layer excite magnons in the antiferromagnetic insulator, generating a magnon current that subsequently exerts magnon torque on an adjacent ferromagnetic layer^{33–35}. This approach presents an attractive pathway toward more energy-efficient spintronic devices³⁶. More importantly, this magnon-mediated spin torque can leverage the symmetry of the antiferromagnetic layer, offering an additional degree of freedom for spin torque engineering. Recent studies have shown that the amplitude of magnon torque can be tuned by controlling the ferroelectric order in a heterostructure incorporating multiferroic BiFeO₃^{37–39}. However, controlling the direction of magnon spin polarization to generate unconventional magnon torques remains unexplored.

In this work, we experimentally demonstrate that two-variant ferroelectric domains with distinct spin cycloid structure in BiFeO₃ enable control over magnon spin polarization (Fig. 1c). In epitaxial SrRuO₃/BiFeO₃/Ni₈₀Fe₂₀ heterostructures, we observe efficient generation of unconventional magnon torque $\tau_{DL}^x \propto \mathbf{M} \times (\mathbf{x} \times \mathbf{M})$, with spin polarization rotated by up to 11° from the conventional y -axis direction dictated by symmetry. This unconventional magnon torque strongly depends on the orientation of the ferroelectric domains and is absent in samples with disordered domains, consistent with the symmetry analysis of BiFeO₃, which possesses ferroelectrically coupled spin cycloid structures. We further demonstrate deterministic, field-free magnetization switching along the x -axis which is prohibited by symmetry with conventional spin torque. These results reveal that control of the ferroelectric domain structures in multiferroic materials provides a route to leverage hidden symmetries within the antiferromagnetic order, opening pathways for advanced functionalities in future magnon-based spintronic devices.

Results

Symmetry analysis of BiFeO₃ with spin cycloid structure

Bulk BiFeO₃ possesses a pseudocubic perovskite lattice with a slight rhombohedral distortion⁴⁰. The breaking of inversion symmetry in BiFeO₃ induces robust ferroelectric polarization $\mathbf{P}^{41}$ (approximately 100 $\mu\text{C}/\text{cm}^2$) oriented along one of the eight possible pseudocubic $[111]$ directions, forming eight ferroelectric variants ($\mathbf{P}_i^\pm$), as illustrated in Fig. 2a. These eight ferroelectric variants give rise to three possible types of ferroelectric domain walls (71°, 109° and 180°)⁴². The inversion

symmetry breaking also leads to a strong Dzyaloshinskii–Moriya (DM) interaction characterized by a pseudovector $\mathbf{D}$ that is perpendicular to $\mathbf{P}^{37}$. For instance, when $\mathbf{P}$ points along $[111]$, $\mathbf{D}$ oriented along $[11\bar{2}]$ cants the antiferromagnetically coupled Fe³⁺ magnetic moments, leading to a spin cycloid structure that couples strongly to the magnon band structure and magnon transport^{43–46}. This cycloid rotates within the plane perpendicular to $\mathbf{D}$ and propagates along the vector $\mathbf{k}$ $[1\bar{1}0]$ ⁴¹, satisfying the orthogonality condition $\mathbf{D} \propto \mathbf{P} \times \mathbf{k}$, as illustrated in Fig. 2b. Another intrinsic DM interaction parallel to $\mathbf{P}$ accounts for non-compensation of the magnetic moments in BiFeO₃, though this contribution is relatively small^{47,48}. Therefore, the chirality of the Fe³⁺ spin cycloid is predominantly determined by $\mathbf{D}$. The cycloidal rotation in BiFeO₃ can be described by a pseudovector $\mathbf{\Omega}_n = (\mathbf{n} \cdot \mathbf{k})\mathbf{D}^{49}$ ($\mathbf{n}$ denotes an arbitrary real-space direction).

We exploit the symmetries of the cycloidal spin structure to control magnon-mediated spin currents by engineering the ferroelectric domain structure in BiFeO₃. In the two-variant domain BiFeO₃ that can be stabilized through strain⁵⁰ or substrate vicinity⁵¹, the cycloidal propagation vector $\mathbf{k}$ is constrained within the sample plane and remains orthogonal to $\mathbf{P}^{50,52}$. As illustrated in Fig. 2c, domain 1 exhibits polarization $\mathbf{P}_1^-$ along $[1\bar{1}\bar{1}]$, $\mathbf{k}_1$ along $[1\bar{1}0]$, and $\mathbf{D}_1$ along $[1\bar{1}\bar{2}]$; similarly, domain 2 exhibits polarization $\mathbf{P}_2^-$ along $[11\bar{1}]$, $\mathbf{k}_2$ along $[110]$, and $\mathbf{D}_2$ along $[11\bar{2}]$.

To understand the symmetry implications of this two-variant domain structure for magnon-mediated spin transport, we perform a symmetry analysis by considering symmetry operations $\mathcal{O}$ acting on the cycloidal antiferromagnetic order⁴⁹ (Fig. 2d). The identity operations show the directions of vectors in each domain. Because $\mathbf{P}$ inherently breaks the four-fold symmetry about the $[001]$ axis, we focus our analysis on mirror operations ($\mathcal{M}_{[100]}$, $\mathcal{M}_{[010]}$ and $\mathcal{M}_{[001]}$) defined relative to planes perpendicular to the pseudocubic axes $[100]$, $[010]$, and $[001]$, as well as an out-of-plane two-fold rotation operation along the $[001]$ axis ($\mathcal{C}_{[001]}^2$). We investigate how these operations affect the cycloidal rotation pseudovectors $\mathbf{\Omega}_{[100]}$, $\mathbf{\Omega}_{[010]}$, and $\mathbf{\Omega}_{[001]}$, as these vectors determine magnon chirality via DM interactions³⁷. We find that $\mathcal{M}_{[100]}$, $\mathcal{M}_{[001]}$, and $\mathcal{C}_{[001]}^2$ are not valid symmetries for the two-variant domain structure, as they alter the cycloidal rotation vectors $\mathbf{\Omega}_{[100]}$, $\mathbf{\Omega}_{[010]}$, and $\mathbf{\Omega}_{[001]}$. In contrast, the mirror operation $\mathcal{M}_{[010]}$ swaps the cycloid rotation between domains relative to the identity operation (Fig. 2c, d). Therefore, the combination of $\mathcal{M}_{[010]}$ with a half-period translation symmetry constitutes the

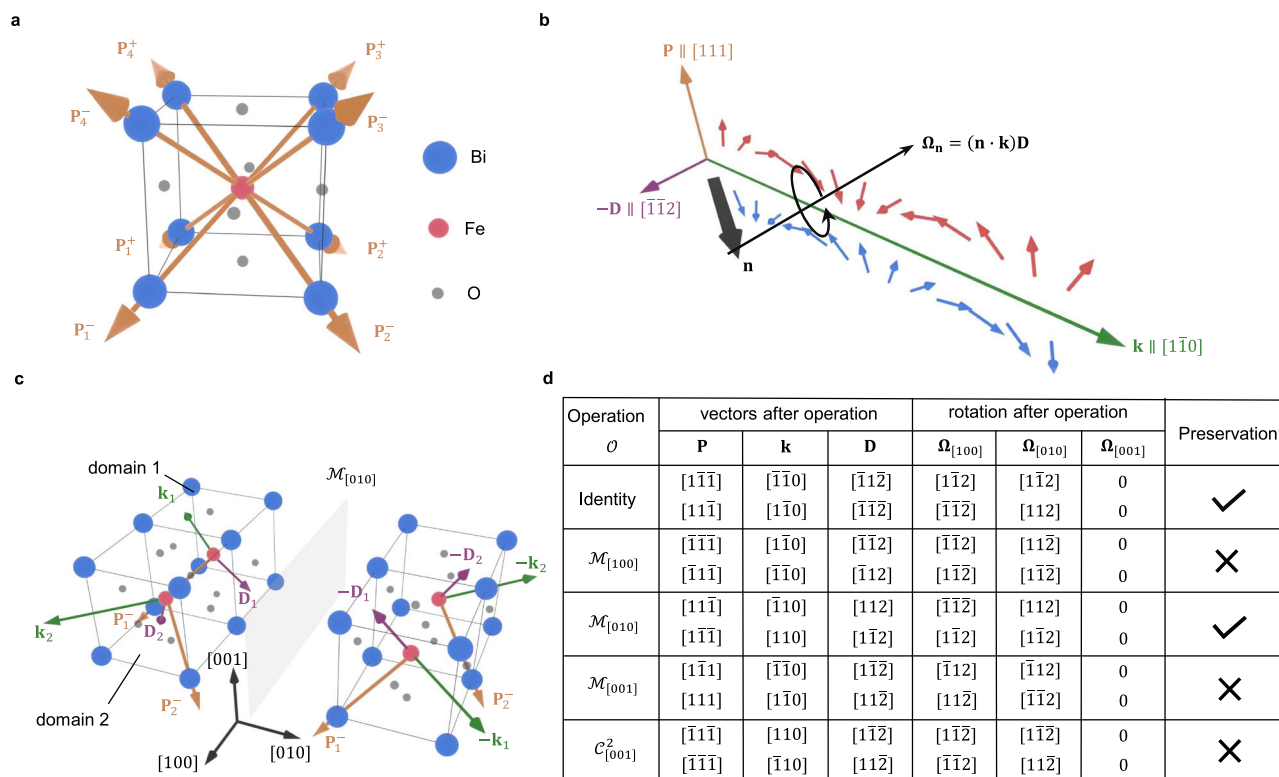


Fig. 2 | Symmetry breaking of spin cycloid rotation in BiFeO₃ with a two-variant domain structure. **a** Schematic of the pseudo-cubic crystalline structure of BiFeO₃, showing eight possible ferroelectric polarization variants $\mathbf{P}_i^\pm$ (orange arrows) along equivalent $[111]$ directions. **b** Schematic of the typical spin cycloid structure in BiFeO₃ with $\mathbf{P}$ oriented along $[111]$. A DM vector $\mathbf{D}$ (the purple arrow) along $[112]$ cant the antiferromagnetically coupled Fe^{3+} magnetic moments, resulting in a cycloidal rotation characterized by the propagation direction $\mathbf{k}$ (the green arrow) along $[110]$. The cycloidal rotation along an arbitrary direction $\mathbf{n}$ is described by the vector $\Omega_{\mathbf{n}} = (\mathbf{n} \cdot \mathbf{k})\mathbf{D}$. **c** Illustration of the two-variant domain structure with $\mathbf{P}_1^-$ (in domain 1) and $\mathbf{P}_2^-$ (in domain 2) under a mirror symmetry operation $\mathcal{M}_{[010]}$ (gray plane). In each domain, $\mathbf{k}_1$ ($\mathbf{k}_2$) and $\mathbf{D}_1$ ($\mathbf{D}_2$) are labeled corresponding to $\mathbf{P}_1^-$ ($\mathbf{P}_2^-$),

respectively. After the mirror operation $\mathcal{M}_{[010]}$, the original crystalline structure (left) is mirrored (right), swapping $\mathbf{P}$ between the domains, i.e., $\mathbf{P}_1^-$ mirrored into $\mathbf{P}_2^-$ and vice versa. The corresponding $\mathbf{k}_1$ ($\mathbf{k}_2$) and $\mathbf{D}_1$ ($\mathbf{D}_2$) are also swapped with their counterparts in the other domain, but with directions reversed, and as a result, $\Omega_{\mathbf{n}}$ is swapped between the domains. **d** Table summarizing the effects of various symmetry operations on $\mathbf{P}$, $\mathbf{k}$, and $\mathbf{D}$ in each domain, as well as the corresponding cycloid components $\Omega_{[100]}$, $\Omega_{[010]}$, and $\Omega_{[001]}$, respectively. Blue check marks indicate that the global spin cycloid symmetry under $\mathcal{M}_{[010]}$ (combined with translation by half a domain period) is preserved, making it equivalent to the identity operation.

only valid symmetry for the system. This low-symmetry configuration permits an unconventional in-plane damping-like torque of the form $\tau_{\text{DL}}^x \propto \mathbf{M} \times (\mathbf{x} \times \mathbf{M})$, provided that the applied charge current is neither parallel nor perpendicular to the $[010]$ axis¹⁶. We also analyzed the symmetry of other achievable domain structures (see Supplementary Note 1).

Measurement of unconventional magnon torque

To experimentally confirm the presence of unconventional magnon torque, we fabricated epitaxial heterostructures consisting of 11 nm SrRuO₃/40 nm BiFeO₃/5 nm Ni₈₀Fe₂₀ on orthorhombic (o) DyScO₃ substrates with $(110)_o$ orientation (see Methods). The slight in-plane compressive strain introduced by the $(110)_o$ -oriented DyScO₃ substrate leads to a well-defined, two-variant ferroelectric domain structure in BiFeO₃, separated by 71° domain walls⁵⁰. A bulk-like spin cycloid structure in the BiFeO₃ thin film is stabilized, with propagation vectors $\mathbf{k}_1$ ($[\bar{1}\bar{1}0]$) and $\mathbf{k}_2$ ($[1\bar{1}0]$) corresponding to the two domain variants⁵³. SrRuO₃, exhibiting significant spin Hall conductivity, serves as the spin-source layer that excites magnons in the BiFeO₃^{54–57}. The crystalline quality of the SrRuO₃ and BiFeO₃ layers was characterized by X-ray diffraction (XRD), and the two-variant domain structure was characterized using reciprocal space mapping (RSM) and piezoelectric force microscopy (PFM) (see Supplementary Fig. 2), consistent with previous studies⁵⁰. All spin torque measurements were performed at room temperature, well above the Curie temperature of SrRuO₃ (–160 K).

To quantify the magnon torque, we employed spin-torque ferromagnetic resonance (ST-FMR) measurements (see Methods). Devices were patterned as microstrips (16 μm wide and 80 μm long) aligned along various crystalline orientations, characterized by the angle φ_E between the applied microwave current I_{RF} direction and the $[100]$ axis (Fig. 3a). Since the device dimensions are much larger than individual ferroelectric domains (about 200 nm)⁵⁰, the measured magnon torque reflects the overall symmetry of the two-variant domain structure. For ST-FMR measurements, I_{RF} with a fixed frequency f was applied, and the external magnetic field H was swept in-plane at different angles φ_H relative to the current axis.

A representative ST-FMR spectrum for the $\varphi_E = 45^\circ$ device at $\varphi_H = 40^\circ$ is shown in Fig. 3b. The symmetric V_s and antisymmetric V_A voltage components were extracted using Eq. (1) in Methods. To differentiate conventional and unconventional magnon torque contributions, we analyzed the magnetic angular φ_H dependence of the voltage signal components^{17,22} (see Eqs. (2) and (3) in Methods). For the $\varphi_E = 0^\circ$ device (I_{RF} along $[100]$), the angular dependence of the symmetric voltage V_s can be described by the form $\cos \varphi_H \sin 2\varphi_H$ (Fig. 3c), corresponding exclusively to a conventional damping-like torque τ_{DL}^y . This behavior is consistent with symmetry constraints that forbid unconventional magnon torque generation when the current is aligned with the mirror plane $\mathcal{M}_{[100]}$.

In contrast, the $\varphi_E = 45^\circ$ device shows a distinctly different angular dependence (Fig. 3d), in which the fitting of V_s requires

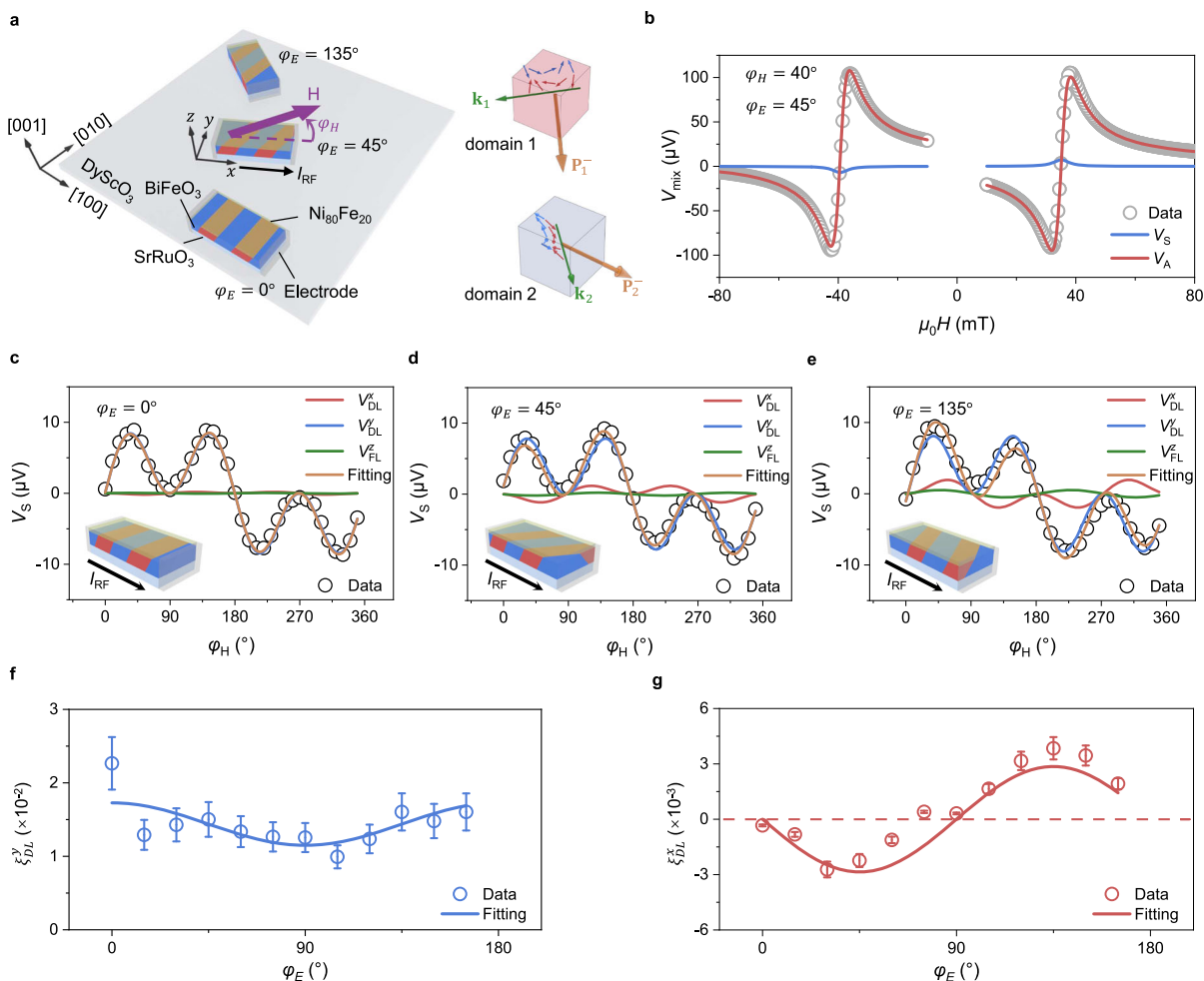


Fig. 3 | Measurement of unconventional multiferroic magnon torque.

a Schematic illustrating three representative devices of 11 nm SrRuO₃/40 nm BiFeO₃/5 nm Ni₈₀Fe₂₀ with microwave charge current I_{RF} applied at angles 0°, 45° and 135° relative to the [100] direction. Red and blue blocks represent the two ferroelectric variants (domain 1 and domain 2) in BiFeO₃, with associated spin cycloid propagation vectors $\mathbf{k}_1$ and $\mathbf{k}_2$, respectively. **b** ST-FMR spectrum measured at frequency $f = 5$ GHz and field angle $\varphi_H = 40^\circ$ for the device with $\varphi_E = 45^\circ$.

c–e Angle φ_H dependence of the symmetric ST-FMR voltage component V_S for devices with I_{RF} aligned at 0° (c), 45° (d), and 135° (e) relative to the [100] direction. Insets show the relative orientation of I_{RF} and the two-variant domain structure. **f** Dependence of the conventional damping-like torque efficiency ξ_{DL}^y on the angle φ_E , fitted to $\xi_{\text{DL}}^y = \xi_y^0 + \xi_y \cdot \cos^2(\varphi_E)$ (blue solid line). **g** Dependence of the unconventional damping-like torque efficiency ξ_{DL}^x , fitted to $\xi_{\text{DL}}^x = \xi_x^0 \cdot \sin(2\varphi_E)$ (red solid line). Red dashed lines indicate the baseline $\xi_{\text{DL}}^x = 0$.

including an additional component proportional to $\sin \varphi_H \sin 2\varphi_H$, consistent with an unconventional damping-like torque τ_{DL}^x with spin polarization along the x -axis (σ_x). Notably, this unconventional component $\sin \varphi_H \sin 2\varphi_H$ reverses sign for the $\varphi_E = 135^\circ$ device (Fig. 3e). In all devices, the V_A components were consistent with conventional out-of-plane field-like torque $\tau_{\text{FL}} \propto \mathbf{M} \times \mathbf{y}$ (Supplementary Note 3 and Supplementary Fig. 3).

We then systematically characterized the damping-like torque efficiencies, ξ_{DL}^y (conventional torque with σ_y) and ξ_{DL}^x (unconventional torque with σ_x) across devices with φ_E varying from 0° to 165° (Supplementary Note 4 and Supplementary Figs. 4 and 5). The dependences of ξ_{DL}^y on φ_E show modest $\cos^2(\varphi_E)$ anisotropy, attributed to the orthorhombic symmetry of the DyScO₃ substrate⁵⁴, with magnitudes consistent with previously reported magnon torque efficiencies in similar SrRuO₃ systems (Fig. 3f)^{38,39,54,55}. The unconventional torque efficiency ξ_{DL}^x reaches a maximum at $\varphi_E = 45^\circ$ and 135° , well fitted to $\sin(2\varphi_E)$ anisotropy (Fig. 3g), consistent with our symmetry analysis (see Fig. 2). The uncertainties for the torque efficiencies come mainly from possible layer-thickness variations, see the analysis in Supplementary Note 5, Supplementary Fig. 6. The maximum ratio of $\xi_{\text{DL}}^x/\xi_{\text{DL}}^y$ (20%) corresponds to an approximately 11° rotation of the spin polarization from the conventional y -axis direction, comparable to

values reported in low symmetry spin-source materials^{12–24}. Independent second harmonic Hall measurements performed on the same sample further confirmed the angular (φ_E) dependence of both τ_{DL}^y and τ_{DL}^x consistent the ST-FMR results (see Supplementary Note 6, Supplementary Figs. 7 and 8).

To confirm the role of the ferroelectric domains in enabling unconventional torque, we fabricated a control sample with a thinner BiFeO₃ layer (11 nm SrRuO₃/20 nm BiFeO₃/5 nm Ni₈₀Fe₂₀ on (110)_o-oriented DyScO₃ substrate), in which the ferroelectric domain structure collapses into a disordered state due to reduced crystal anisotropy or random pinning⁴². We found that ξ_{DL}^x fluctuates near the noise level, indicating negligible τ_{DL}^x (see Supplementary Note 7 and Supplementary Fig. 9). Additional control measurements ruled out contributions from either SrRuO₃ or BiFeO₃ alone in heterostructures of 11 nm SrRuO₃/5 nm Ni₈₀Fe₂₀ and 40 nm BiFeO₃/5 nm Ni₈₀Fe₂₀ grown on (110)_o-oriented DyScO₃ substrates (see Supplementary Notes 8 and 9, Supplementary Figs. 10 and 11). These experimental results demonstrate that the symmetry of ferroelectric domains dominates the τ_{DL}^x generation, likely through the exchange interaction between the injected magnon current and the noncollinear spin texture^{37,38,43} and can potentially be extended to other multiferroic materials^{58,59}.

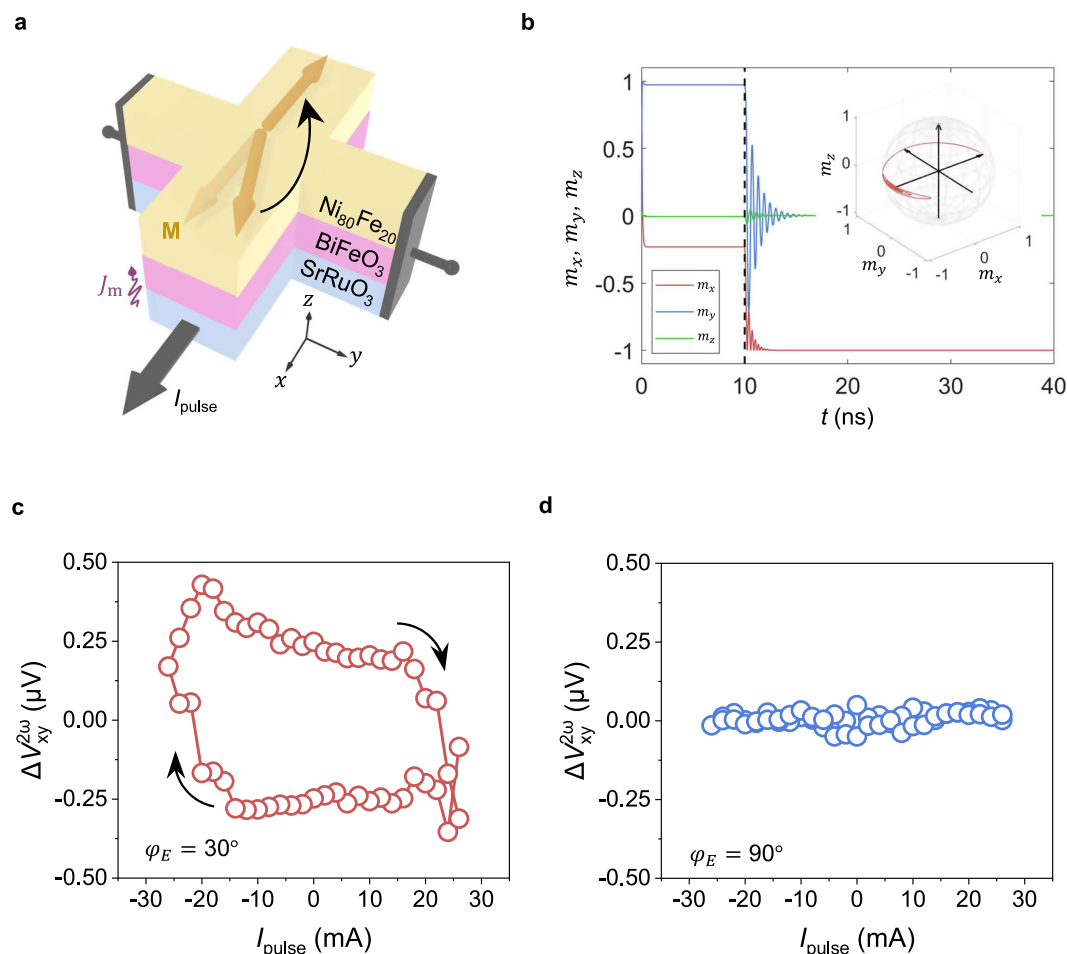


Fig. 4 | Field-free type-x magnetization switching induced by unconventional magnon-torque. **a** Schematic of field-free type-x magnetization switching. The black curve indicates the magnetization trajectory during the switching process. **b** Simulated time evolution of the normalized magnetization components m_x, m_y, m_z driven by magnon spin current J_m with a nonzero τ_{DL}^x , in the absence of an external magnetic field. The starting magnetization orientation is $m_x = +1$. The

inset shows the snapshot of the switching trajectory (red line). The black dashed line marks the 10 ns duration of the applied current pulse in the macro-spin simulation. **c** Current-induced field-free magnetization switching in a Hall bar device oriented at $\varphi_E = 30^\circ$, where the symmetry permits the generation of unconventional torque τ_{DL}^x . **d** Absence of field-free magnetization switching in a Hall bar device with $\varphi_E = 90^\circ$, in which τ_{DL}^x is forbidden by symmetry.

Deterministic, field-free type-x magnetization switching

Finally, we demonstrate that this unconventional magnon torque τ_{DL}^x can drive deterministic field-free switching of magnetization along the x -axis (referred to as type-x switching), as schematically shown in Fig. 4a. Conventionally, deterministic type-x switching using damping-like torque τ_{DL}^y requires an external out-of-plane magnetic field to break symmetry⁶⁰. To understand the role of τ_{DL}^x in switching dynamics, we performed macro-spin simulations for field-free type-x switching, incorporating a damping-like magnon torque with an in-plane spin polarization canted by 11° , consistent with that observed in our sample (see Methods). Figure 4b shows the simulated trajectories of magnetization with initial magnetization along $+x$ direction. Under a 1 ns current pulse, magnetization aligns toward the direction of σ , with suppressed precessional amplitudes due to damping cancellation by τ_{DL}^x . Upon pulse termination at 10 ns, the magnetization relaxes into the $-x$ direction, resulting in deterministic, field-free switching. Control simulations without σ_x failed to produce switching, confirming the critical role of τ_{DL}^x for enabling type-x switching (see Supplementary Note 10 and Supplementary Fig. 12).

We then experimentally validated the field-free type-x switching in the 11 nm SrRuO_3 /40 nm BiFeO_3 /5 nm $\text{Ni}_{80}\text{Fe}_{20}$ sample. To monitor the magnetization state, we utilized the second-harmonic Hall

voltage ($V_{xy}^{2\omega}$), which arises from the spin Seebeck effect (SSE)⁶¹ in the $\text{Ni}_{80}\text{Fe}_{20}$ layer due to a thermal gradient ∇T perpendicular to the sample plane. This generates a spin current with spin polarization parallel to the magnetization, which propagates through the BiFeO_3 and produces $V_{xy}^{2\omega} \propto \nabla T \times \mathbf{M}_x$ in SrRuO_3 via the inverse spin Hall effect⁶². An example of a hysteresis loop in $V_{xy}^{2\omega}$, corresponding to the reversal of $\mathbf{M}_x$ in response to sweeping an in-plane field along the x -axis is presented in Supplementary Note 11 and Supplementary Fig. 13.

Figure 4c shows deterministic, field-free switching of $\mathbf{M}_x$ driven by a 500 μs current pulse I_{pulse} , in a Hall bar device oriented at $\varphi_E = 30^\circ$, where symmetry permits the unconventional magnon torque τ_{DL}^x . (Shape anisotropy causes the magnetic easy axis to be in the x direction.) The critical switching current is about 22 mA, corresponding to a current density of about $4.6 \times 10^6 \text{ A/cm}^2$ (Supplementary Note 4). The switching polarity is reversed for the $\varphi_E = 135^\circ$ device (see Supplementary Fig. 14), consistent with the reversal of τ_{DL}^x . In contrast, no field-free switching is observed in Hall bar devices with $\varphi_E = 90^\circ$ (Fig. 4d), where symmetry forbids the generation of unconventional torque τ_{DL}^x . In this case, magnetization reversal requires a 3 mT out-of-plane magnetic field (Supplementary Fig. 13). The realization of field-free type-x switching enabled by magnon current in BiFeO_3 could

provide potential for developing high-density, energy efficient and fast-switching magnetic devices (see Supplementary Note 12, Supplementary Fig. 15 and Supplementary Table 1).

Discussion

We have demonstrated an unconventional magnon torque in heterostructures based on multiferroic BiFeO₃. By engineering the ferroelectric domain structure and leveraging the spin-cycloid ordering of BiFeO₃, we reduced the system's symmetry and overcame the geometric constraints typically imposed on spin-torque polarization. Through systematic ST-FMR and second harmonic Hall measurements performed on SrRuO₃/BiFeO₃/Ni₈₀Fe₂₀ devices with a well-defined two-variant ferroelectric domain structure, we observed unconventional magnon torque with spin polarization rotated up to 11° away from the conventional symmetry-constrained *y*-axis. This symmetry-engineered unconventional magnon torque enables deterministic, field-free type-*x* magnetization switching.

Symmetry analysis indicates that controlling the crystallinity of BiFeO₃ offers a route to flexibly modulate magnon spin polarization. In addition, the intrinsic switchability of ferroelectric polarization in BiFeO₃ presents a pathway for non-volatile, electric-field control of these unconventional magnon torques. These findings establish a new platform for exploring advanced magnonic device functionalities enabled by multiferroic materials.

Methods

Sample growth

Epitaxial SrRuO₃/BiFeO₃ heterostructures were deposited on (110)_o-oriented DyScO₃ substrates using pulsed laser deposition (PLD) with a 248 nm KrF excimer laser. SrRuO₃ and BiFeO₃ were deposited at substrate temperatures of 670 °C and 700°C, under an oxygen partial pressure of 110 mTorr and 150mTorr, respectively. The laser fluence at the target surfaces was approximately 1.5 J/cm² with a pulse repetition rate of 5-7 Hz. Subsequently, the samples were cooled to room temperature in an oxygen-rich atmosphere and transferred through air to a magnetron sputtering chamber with a base pressure of 1×10⁻⁸ Torr for the deposition of ferromagnetic metals. The ferromagnetic Ni₈₀Fe₂₀ layer was deposited at an argon pressure of 3 mTorr, followed by a 3 nm Ti capping layer to prevent oxidation. Film thicknesses were measured using X-ray reflectivity.

Device fabrication

Devices for ST-FMR and second-harmonic Hall measurements were fabricated on the same sample chip using standard photolithography, followed by argon-ion milling. Subsequently, 10 nm Ti / 150 nm Cu bilayers were deposited for electrode contacts using a standard lift-off process. ST-FMR devices were patterned into 16μm-wide and 80μm-long microstrips with ground-signal-ground (GSG) electrodes, while devices for second harmonic Hall measurements were patterned into 16μm-wide and 80μm-long Hall bars with 4μm-wide Hall contacts.

Magnon torque measurements

For ST-FMR measurements, a Keysight E8257D microwave generator was used to provide a 15 dBm microwave excitation, modulated by an internal oscillator at 1713 Hz. The mixing voltage signal was detected using a DSP 7265 lock-in amplifier. For second harmonic Hall measurements, an AC current at 2333 Hz was supplied by the internal voltage source of the DSP 7265 lock-in amplifier. Both the first- and second-harmonic Hall voltage signals were simultaneously recorded using a single DSP 7265. Magnetic fields for both ST-FMR and second harmonic Hall measurements were applied using a GMW projected-field magnet mounted on a Newport motion-controlled stage.

Vector components of magnon torque extracted from ST-FMR measurements

The alternating magnon torque acting on the Ni₈₀Fe₂₀ layer induces magnetization precession and leads to resistance oscillation due to the device's anisotropic magnetoresistance. Mixing between the device resistance oscillation and *I*_{RF} generates a resonance in the d.c. voltage *V*_{mix}, expressed as⁶³:

$$V_{\text{mix}} = V_S \frac{\Delta^2}{(\mu_0 H - \mu_0 H_0)^2 + \Delta^2} + V_A \frac{\Delta(\mu_0 H - \mu_0 H_0)}{(\mu_0 H - \mu_0 H_0)^2 + \Delta^2} \quad (1)$$

where Δ is the resonant linewidth, μ_0 is the vacuum permeability, and H_0 is the magnet resonant field. V_S and V_A are the symmetric and antisymmetric coefficient of the Lorentzian functions, related to the in-plane and out-of-plane magnon torques, respectively.

If the magnon carries spin polarization components σ_x , σ_y and σ_z , along the *x*, *y*, and *z* axis, respectively, the induced magnon torque has components along all of the *x*, *y*, and *z* axis. The corresponding angle ϕ_H dependences for the V_S and V_A coefficients are expressed as²²:

$$V_A = V_{FL}^x \sin \phi_H \sin 2\phi_H + V_{FL}^y \cos \phi_H \sin 2\phi_H + V_{DL}^z \sin 2\phi_H \quad (2)$$

$$V_S = V_{DL}^x \sin \phi_H \sin 2\phi_H + V_{DL}^y \cos \phi_H \sin 2\phi_H + V_{FL}^z \sin 2\phi_H \quad (3)$$

Here, V_{DL}^x , V_{DL}^y , and V_{DL}^z are coefficients for the damping-like torque generated by the σ_x , σ_y and σ_z , respectively. V_{FL}^x , V_{FL}^y , and V_{FL}^z are the field-like-torque counterparts. We note that V_{FL}^y , in principle, can have contributions from both a field-like magnon torque and a current-induced Oersted field.

Macrospin simulation

We performed macro-spin simulation of type-*x* magnetization switching by numerically solving spin-orbit torque modified LLG equation with damping-like torque⁶⁴⁻⁶⁶:

$$\frac{\partial \mathbf{m}}{\partial t} = \gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \gamma H_{DL} (\mathbf{m} \times \boldsymbol{\sigma} \times \mathbf{m}) \quad (4)$$

where $\mathbf{m}$ is the unit magnetization, which can be written as (m_x, m_y, m_z), γ is the gyromagnetic ratio, $\mathbf{H}_{\text{eff}} = \frac{\delta(-H_k^x(\mathbf{m} \cdot \mathbf{x})^2 - H_k^z(\mathbf{m} \cdot \mathbf{z})^2)}{\delta \mathbf{m}}$ is the effective field mainly contributed by the anisotropy field with $\mu_0 H_k^x = 5$ mT, $\mu_0 H_k^z = 0.8$ T. $\alpha = 0.014$ is the Gilbert damping coefficient, H_{DL} is the damping-like torque effective field induced by magnon-mediated spin current $\mathbf{J}_m = \xi \mathbf{J}_c \boldsymbol{\sigma}$ with $\boldsymbol{\sigma} = (-\sin \psi, \cos \psi, 0)$ as the normalized spin polarization and $\psi = 11^\circ$. A magnon torque efficiency of $\xi = 0.015$ was extracted from the device capable of achieving field-free type-*x* switching. In our simulation, $\mathbf{J}_c = 1.1 \times 10^6$ A/cm², which is on the same order of magnitude as the experimental current density required for magnetization switching.

Magnon-torque-induced magnetization switching measurements

Field-free magnetization switching induced by magnon torque was measured using a probe station under zero applied magnetic field. Magnetization switching assisted by an out-of-plane magnetic field, as described in Supplementary Note 11, was performed in a Physical Property Measurement System (PPMS). All measurements were conducted at room temperature. A Keithley 6221 source meter was used to generate a single square wave with a 1 ms period and a 50% duty cycle, corresponding to a pulse duration of 500 μs. Following the application of the current pulse, the system waited for 8 s before measuring the second-harmonic Hall voltage using a DSP 7265 lock-in amplifier at 2333 Hz and a current amplitude of 2 mA.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Information. Source data are provided with this paper. The data that support the findings of this study are also available in Zenodo with the identifier <https://doi.org/10.5281/zenodo.18623111>.

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Author contributions

T.N., D.C.R., and D.Y. conceived and supervised the experiments. X.Y., X.J., X.Q., H.B., and W.J. performed the sample growth. Y.L. and D.J. performed the device fabrication. Y.L., H.C., D.P., X.H., and R.J. performed device measurements and analysis. Z.W. and D.S. conducted a macro-spin simulation. T.N., D.C.R., D.Y., and Y.L. wrote the manuscript. All authors discussed the results and commented on the manuscript. T.N., D.C.R., and D.Y. directed the research.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Di Yi, Daniel C. Ralph or Tianxiang Nan.

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