Direct visualization of magnetoelectric domains

Yanan Geng¹, Hena Das², Aleksander L. Wysocki², Xueyun Wang¹, S-W. Cheong¹, M. Mostovoy³, Craig J. Fennie², and Weida Wu¹*

¹Department of Physics and Astronomy and Rutgers Center for emergent materials, Rutgers University, Piscataway, NJ 08854 USA
²School of Applied and Engineering Physics, Cornell University, Ithaca, NY, 14853, USA
³Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG, Groningen, Netherlands

Methods

Plate-like $h$-ErMnO$_3$ single crystals with flat surfaces perpendicular to the $c$ axis were grown by a conventional flux method with Bi$_2$O$_3$ flux. A mixture of 80 mol % of Bi$_2$O$_3$ and 20 mol % of $h$-ErMnO$_3$ powders was heated up to 1260 °C in a platinum crucible, and cooled slowly with 2.5 °C/h rate. Two pieces from the same batch were heated again up to 1200 °C, and slowly cooled to 1130 °C with 15 °C/h. One piece is used in SQUID measurement, the other is used in PFM and MeFM experiments. The specimen (thickness ~200 μm) was glued to a sapphire substrate by Ag epoxy, which also serves as the bottom electrode.

Ambient PFM images were taken on the bare (001) surface with a Multimode atomic force microscope (Bruker) interfaced with homemade circuits. After PFM measurements, a thin gold film (~50 nm) was deposited onto the top (001) surface using magnetron sputtering before MeFM experiments. The MeFM setup is based on a home-made cryogenic MFM ¹⁻³, which is interfaced with a Nanoscope IIIa controller and a Nanonis phase-locked loop (SPECS). Using a Nanonis high voltage amplifier, AC high voltages (10 – 300 Hz, $V_{pp}$ ~ 600 V) was applied to the bottom electrode. The MeFM signal was taken in a constant height (~100 nm) mode after topography measurements. The demodulated MFM signal is fed to the

* Corresponding author: wdwu@physics.rutgers.edu.
input of a lock-in amplifier (SR830) and the in-phase signal (from the x-channel) is recorded as the MeFM image. During MeFM experiments, the sample space was kept in cryogenic high vacuum (<10^{-6} mbar) for high sensitivity detection. The alignment between PFM and MeFM images was achieved by correlating topographic features.

The first principles calculations were performed using the DFT+U method \(^4\) with the PBE form of the exchange-correlation functional \(^5\). For Mn 3d states we used U = 4.5 eV and J_H = 0.95 eV. The partially filled Er 4f states were put in the core. The Kohn-Sham equations were solved using the projector augmented wave method as implemented in the VASP code \(^6,7\). We used a 4×4×2 k-point mesh and a kinetic energy cut-off of 500 eV. Structural relaxations and electric polarization calculations were performed without the spin-orbit coupling (SOC) while the magnetization was calculated in the presence of SOC.
Discussion 1  Control experiments of MeFM measurement

We have performed several control experiments to confirm that our MeFM signal is purely from the $E$-induced magnetization ($M_E$).

First, our MFM does not detect any electric field from ferroelectric domains, as the latter is screened by the top electrode (Au film). The lack of MeFM signal at zero field and the significant $H$-dependence of MeFM contrast also excludes the electrostatic origin.

Second, piezoelectric response induced tip-surface distance modulation can be excluded because of the weakness of $d_{33} (<1 \text{ pm/V})$ of hexagonal manganites and the cancellation of $d_{33}$ due to the random stacking of ferroelectric domains along the $c$-axis.

Third, the MeFM contrast is linearly proportional to the amplitude of applied $E$ field, as shown in Fig. S1.

Fourth, the magnitude and the phase of MeFM signal are independent of the modulation frequency, excluding the possibility of the contamination from static magnetic signal.

Furthermore, we observed the expected giant magnetoelectric response in magnetoelectric orthoferrite DyFeO$_3$ using our MeFM. The $T$-dependence of the MeFM signals shown in Fig. S2, were measured on (001) surface of a single crystal DyFeO$_3$ after preparing bulk single domain states with different ME annealing conditions.

Finally, we observed similar domain contrast and $H$-dependence in $h$-ErMnO$_3$ single crystals with a stripe domain pattern. PFM image and typical MeFM images at the same location are shown in Fig. S3. This demonstrates that the magnetoelectric effect and the clamping of ferroelectric, structural anti-phase and antiferromagnetic orders in $h$-ErMnO$_3$ are independent of domain structure.
Figure S1 | Linear electric field dependence of the MeFM signal. E-field dependence of the MeFM contrast at various representative magnetic field and temperature points.

Figure S2 | T-dependence of the linear magnetoelectric effect of DyFeO₃ after ME annealing. A single magnetoelectric domain state can be prepared after the magnetoelectric annealing i.e., cooling the sample with different E and H fields through the ordering temperature. The combination of the annealing E and H fields determines the sign of the magnetoelectric coupling coefficient, and the amplitude scales with the antiferromagnetic order parameter below $T_N$. In this control experiment, the $T$-dependences of the magnetoelectric effects in DyFeO₃ ($T_N^{\text{Dy}} \sim 3.5$ K) were measured with MeFM after different magnetoelectric annealing conditions ($E = +/-10$ kV/cm, $\mu_0H = 1.0$T). Our results are consistent with the previous studies $^9$. 
Figure S3 | PFM and MeFM results of \( h \)-ErMnO\(_3\) with stripe domain pattern. a, room temperature PFM image of the (001) surface of a \( h \)-ErMnO\(_3\) single crystal with stripe domain pattern. The white (dark) color in PFM image represents up (down) ferroelectric domain. b-d, low temperature (5 K) MeFM images were taken at the same location at 0.1, 4.0, and 6.0 T, respectively.

Figure S4 | MeFM images in opposite magnetic fields. The canted moment \( M_z \) is reversed in opposite magnetic fields, resulting in opposite magnetoelastic coefficient between a and b. At the same time, the direction of the MFM tip moment \( M_{\text{tip}} \) follows that of applied magnetic field. Hence, the image contrasts are identical for opposite magnetic fields, as shown in the +4 T and −4 T MeFM images.
### Figure S5 | Symmetry analysis of phenomenological Landau free energy of the A2 phase.

The table shows symmetry transformations of the allowed linear magnetoelectric term \( J^{\text{ME}} = \cos(3\Phi) L_{\chi} H_z E_z \) in the Landau free energy expansion of the A2 \((P6_3cm)\) phase under the generators of the \(P6_3/mmc1\) space group of hexagonal manganites. Here we follow the notations of Artyukhin \textit{et al} for the definitions of Mn\(^{3+}\) spin angle \(\psi_{1,2}\) (of even and odd layers of Mn trimmers) and the structural trimerization phase \(\Phi\). The four magnetic states \((A_1, A_2, B_1, B_2)\) of hexagonal manganites with spin directions are indicated by red arrows. \(L_{\chi}\) is the magnetic order parameter describing the symmetry of the A2 phase. It can be formally defined as \(L_{\chi} = \frac{1}{N} \sum_i S_i \cdot n_i\), where \(n_i\) is the unit vector in the spin direction on the Mn site \(i\) in the A2 phase (indicated by red arrows), \(S_i\) is the average spin on the site \(i\) and \(N\) is the total number of Mn sites. For \(T \ll T_N\), the magnetic order parameter of the A2 phase is reduced to \(L_{\chi} = \frac{1}{4} L (\sin \chi_1 + \sin \chi_2)\), where \(L\) is the magnitude of the 120° spin ordering in...
Mn layers. Similarly, the magnetic order parameter of B$_2$ phase is $L_{B_2} = \frac{1}{2} L (\cos\chi_1 + \cos\chi_2)$ at $T \ll T_N$. See Artyukhin et al for detailed discussion of various magnetic states in hexagonal manganites\textsuperscript{10}.

As shown in the table, the free energy term $\cos(3\Phi)L_{A_2}H_zE_z$ is invariant under all generators of the $P6_3/mmc'$ space group, so the linear magnetoelectric coupling is allowed.

$$\alpha_{zz} = -\frac{\partial^2 f^{\text{Me}}}{\partial E_z \partial H_z} \propto \cos(3\Phi)L_{A_2} \propto P_zM_z \quad (S1)$$

Therefore, the coefficient $\alpha_{zz}$ of the A$_2$ phase is proportional to the product of the canted moment $M_z$ and the polarization $P$. This is consistent with our MeFM observation.
To clarify the origin of the diagonal linear magnetoelectric susceptibility ($\alpha_{zz}$) in h-ErMnO$_3$, we consider the phenomenological Landau expansion of the free energy with respect to the $P6_3/mmc1'$ reference structure:

$$f_0 = \frac{1}{2} a_0 Q_{K_1}^2 + \frac{1}{4} b_0 Q_{K_3}^4 + \frac{1}{2} a_p P_z^2 + d_{13} P_z Q_{K_3}^3 \cos 3\Phi + \frac{1}{2} d_{22} P_z^2 Q_{K_3}^3$$

(S2)

to which we add the invariant coupling between the antiferromagnetic order parameter $L_{A_2} = \frac{1}{2} L (\sin \chi_1 + \sin \chi_2)$ of the A$_2$ phase and the magnetic field (see Fig. S5),

$$f_H = -c L_{A_2} Q_{K_1} H_z$$

(S3)

and the interaction with the applied electric field, $f_E = -P_z E_z$. Here we follow the notation of Artyukhin et al. for the definitions of the trimerization phase $\Phi$ and the spin angles $\psi_{1,2}$ (see Fig. S5). Furthermore, $\chi_{1,2} = \psi_{1,2} - \Phi$, while $Q_{K_1}$ and $L$ are the amplitudes of the trimerization and the 120° antiferromagnetic spin order, respectively. The equilibrium magnetization is then given by

$$M_z \equiv -\left. \frac{\partial f}{\partial H_z} \right|_{E_z=0} = c L_{A_2} Q_{K_1}$$

(S4)

In the A$_2$ phase (in high magnetic fields $H > H_c$) the in-plane components of spins are rigid ($\chi_1 = \chi_2 = \frac{\pi}{2}$) so that $L_{A_2} = L$ and $M_z = c L Q_{K_1}$ for weak electric field. The linear magnetoelectric susceptibility is then,

$$\alpha_{zz} \equiv \left. \frac{\partial M_z}{\partial E_z} \right|_{E_z=0} = c L_{A_2} \left. \frac{\partial Q_{K_1}}{\partial E_z} \right|_{E_z=0}$$

(S5)

We note that the electric field dependence of magnetic ordering cannot be neglected in the spin reorientation region (the A$_2'$ phase), where it results in large anomalous magnetoelectric response (see Discussion 5). This anomalous contribution vanishes in the A$_2$ phase.

To find the electric field dependence of $Q_{K_1}$, we minimize $f_0 + f_E$ with respect to $Q_{K_1}$ and $P_z$, and differentiate the coupled equations for these two order parameters with respect to $E_z$ at $E_z=0$, which gives

$$\left. \frac{\partial Q_{K_1}}{\partial E_z} \right|_{E_z=0} = \frac{d_{13} \cos 3\Phi}{d_{22}} \cdot \frac{1}{2a}$$

(S6)
where \( a = a_Q - \frac{d_1}{2a_2} a_P \approx a_Q \). In this derivation we used approximation \( d_{22} Q_{K_1}^2 \gg a_P \). Therefore,

\[
\alpha_{zz} = cL \cdot \frac{d_{13} \cos 3\Phi}{d_{22}} \cdot \frac{1}{2a_Q} \quad \text{(S7)}
\]

Here \( \cos 3\Phi \) determine the sign of \( \alpha_{zz} \) in structural anti-phase domains. It follows that of \( P_z \) because \( P_z \approx -\frac{d_{13}}{d_{22}} Q_{K_1} \cos 3\Phi \). This result can also be obtained by integrating out \( Q_{K_1} \) and \( P_z \) to derive an explicit expression of free energy \( f(E_z, H_z) \), which would naturally contain the corresponding free energy term \( -\alpha_{zz} E_z H_z \) with \( \alpha_{zz} \) given by Eq. (S7).

For quantitative estimation of the magnitude of \( \alpha_{zz} \) in \( h\)-REMnO\(_3\), one needs know the numerical values of the parameters in Eq.(S7). Note that \( cL = \frac{\partial M_z}{\partial Q_{K_1}} \) and \( \frac{d_{13}}{d_{22}} = \frac{\partial P_z}{\partial Q_{K_1}} \) lead to

\[
|\alpha_{zz}| = \left| \frac{1}{2a_Q} \cdot \frac{\partial M_z}{\partial Q_{K_1}} \cdot \frac{\partial P_z}{\partial Q_{K_1}} \right|.
\]

The parameter \( a_Q \) as well as the slopes \( \frac{\partial M_z}{\partial Q_{K_1}} \) and \( \frac{\partial P_z}{\partial Q_{K_1}} \) were extracted from first principles calculations. Here we considered the high-temperature \( P\overline{6}_3/mmc \) structure with the \( A_2 \) magnetic ordering and freezing-in the zone boundary \( K_3 \) mode (the trimerization distortion). The total energy per unit cell\(^{\dagger} \) \( E \), polarization \( P \) and canting magnetization \( M_z \) were computed as a function of the amplitude of the \( K_3 \) mode. The results are shown in Fig S6. The \( E(Q_{K_1}) \) curve was well fitted with the phenomenological Landau free energy expansion \( f_0 = \frac{1}{2} a_Q Q_{K_1}^2 + \frac{1}{4} b_Q Q_{K_1}^4 \), resulting in \( a_Q = -3.50 \text{ eV/Å}^2/\text{(u.c.)} \) and \( b_Q = 5.78 \text{ eV/Å}^4/\text{(u.c.)} \), with energy minimum at \( Q_{K_1}^{\text{min}} \approx 0.778\ Å \). Therefore, we obtained values of the slopes \( \left| \frac{\partial P_z}{\partial Q_{K_1}} \right|_{Q_{K_1}^{\text{min}}} \approx -18.3 \text{ μC/cm}^2/\text{Å} \) and \( \left| \frac{\partial M_z}{\partial Q_{K_1}} \right|_{Q_{K_1}^{\text{min}}} \approx -0.062 \text{ μB/f.u.}/\text{Å} \) from the linear part of the \( P_z(Q_{K_1}) \) and \( M_z(Q_{K_1}) \) curves, respectively. We thus obtain the theoretical estimation of the \( \left| \alpha_{zz}^{\text{th}} \right| \approx 0.7 \text{ ps/m} \).

\(^{\dagger} \) Note that there are 6 formula units of ErMnO\(_3\) (i.e. 6 Mn ions) in one unit cell.
Figure S6 | First principle calculations of the A2 phase of h-ErMnO₃. First principles results: calculated a, Energy (per unit cell), b, polarization (P) and c, canting magnetic moment per formula unit (\(M_z\)) as a function of the amplitude of trimer distortion \(Q_{K1}\).
Figure S7a | Complete data set of MeFM measurements at 2.8 K in various $H$-fields. a, topography of the scanned area. b, PFM image of the same location. c-q, MeFM images of the same location in various magnetic fields (0.3 – 4.0 T). Same color scale for all MeFM images.

Figure S7b | Complete data set of MeFM measurements at 4.0 K in various $H$-fields. a, topography of the scanned area. b, PFM image of the same location. c-q, MeFM images of the same location in various magnetic fields (0 – 8.0 T).
Figure S8 | $H^2$ dependence of the magnetoelectric effect in the high field A$_2$ phase. a, $H$-dependences of MeFM signals at various $T$'s (the same as Fig. 3g). The MeFM signal in the high field A$_2$ phase ($\mu_0 H > 2-3$ T) is well fitted with $\text{MeFM}(H) = a + c(\mu_0 H)^2$ (the solid magenta line) where $a=3.83$ mHz, and $c=0.32$ mHz/T$^2$. b, MeFM vs. $H^2$ of the MeFM($H$) data in the high field A$_2$ phase to demonstrate the $H^2$ dependence is independent of temperature below 10 K.
### Discussion 3  Estimation of the measured $\alpha_{zz}$

The E-field induced magnetization ($M_E$) was estimated by comparing the MeFM signal ($\delta f_{\text{MeFM}}$) with the MFM signal measured on a ferromagnet. Since the MFM signal ($\delta f_{\text{MFM}}$) originates from the dipolar interaction between the MFM tip and the local magnetic domain, the $\delta f_{\text{MFM}}$ signal is approximately proportional to the product of the moment of the MFM tip ($m_{\text{tip}}$) and the magnetization of the local domain ($M_{\text{domain}}$), i.e.

\[
\delta f_{\text{MFM}} \propto m_{\text{tip}} \cdot M_{\text{domain}} \quad (S8)
\]

The same is true for the MeFM signal ($\delta f_{\text{MeFM}}$), i.e.,

\[
\delta f_{\text{MeFM}} \propto m_{\text{tip}} \cdot M_{E} \quad (S9)
\]

By comparing the image contrast of the MeFM images of $h$-ErMnO$_3$ and that of the MFM images of a known ferromagnet, the $M_E$ signal can be estimated as following:

\[
M_E = \frac{\delta f_{\text{MeFM}}}{\delta f_{\text{MFM}}} \frac{m_{\text{tip}(\text{MFM})}}{m_{\text{tip}(\text{MeFM})}} M_{\text{domain}(\text{MFM})} \quad (S10)
\]

Here we used MFM images on a ferromagnetic Fe$_{1/4}$TaS$_2$ ($T_C \sim 160$ K) with strong uniaxial anisotropy. Out-of-plane ferromagnetic domain patterns were observed on single crystals of Fe$_{1/4}$TaS$_2$ after zero field cooling (ZFC) using our homemade cryogenic MFM. A representative MFM image measured at 60 K is shown in Fig. S9. The ratio of the MFM tips’ moments was estimated from MFM measurements on the same reference sample (a magnetic tape) at room temperature. From Eq. (S8), we can obtain the ratio between different tips:

\[
\frac{m_{\text{tip}(\text{MFM})}}{m_{\text{tip}(\text{MeFM})}} = \frac{\delta f_{\text{tip}(\text{MFM})}}{\delta f_{\text{tip}(\text{MeFM})}} \quad (S11)
\]

The tip moment ratio is ~0.275. Using the saturated magnetization of Fe$_{1/4}$TaS$_2$ (1 $\mu_B$/f.u.) for $M_{\text{domain}}$, the MFM image contrast of Fig. S9a ($\delta f_{\text{MFM}} \sim 16.5$ Hz), the intercept value fitting curve in Fig. 3 ($\delta f_{\text{MeFM}} = 3.83$ mHz), the E ($\sim 10^6$ V/m) induced magnetization $M_E$ of $h$-ErMnO$_3$ is estimated to be $6.8 \times 10^{-5}$ ($\mu_B$/f.u.). Therefore, the linear magnetoelectric...
coefficient $\alpha$ of the A$_2$ phase can be estimated using the definition $\alpha = \frac{M_e}{E} \approx 13 \text{ ps/m}$. Similar results (within a factor of 2) were obtained using the same calibration procedure on different Fe$_{1/4}$TaS$_2$ single crystals and other ferromagnetic samples.

Therefore, the order of magnitude of the experimental value of the linear magnetoelectric coefficient is $\alpha_{\text{exp}} \approx 13 \text{ ps/m}$ for the A$_2$ phase of $h$-ErMnO$_3$.

Figure S9 | MFM image of Fe$_{1/4}$TaS$_2$ and the line profile. a, the out-of-plane magnetic domain patterns on the (001) surface of a Fe$_{1/4}$TaS$_2$ single crystal were observed in MFM at 60 K after ZFC. b, a representative line cut of the blue line in a shows the profile of the ferromagnetic domains.

**Discussion 4 Exchange interactions between Mn$^{3+}$ and Er$^{3+}$ spins**

In $h$-ErMnO$_3$, the anisotropic exchange interactions, e.g. the Dzyaloshinskii-Moriya (DM) interactions $^{13,14}$, between the Mn$^{3+}$ and Er$^{3+}$ spins provide an effective exchange field to polarize the Er$^{3+}$ spins. For B$_2$ ($P6_3/m$) phase, Er$^{3+}$ at 4b sites are polarized antiferromagnetically, while the Er$^{3+}$ spin at 2a sites remain disordered due to the zero net DM exchange fields (see Fig. S10a) $^1$. Therefore, the Er$^{3+}$ spins at 2a sites are expected to show paramagnetic behavior, i.e. the $H/T$ scaling. The non-linear magnetoelectric effect ($E_zH_z^2$) at low field likely comes from the $H$-induced Er$^{3+}$ moments at the 2a site.
Figure S10 | Cartoon of anisotropic exchange field induced Er\(^{3+}\) “order” moment and the \(H/T\) scaling of the MeFM signal at low magnetic fields. a, a 3D cartoon of the \(h\)-ErMnO\(_3\) (\(P6_{3}cm\)) crystal structure, where yellow, brown, light blue spheres represent Er, Mn, O atoms, respectively. The black arrows at the 4b sites denote the Er\(^{3+}\) moments polarized by Mn\(^{3+}\) through DM interactions. The red hollow arrow at 2a site describes the paramagnetic spins induced by applied magnetic field. b, the MeFM signal is plotted against \(H/T\) at various \(T\) and \(H\). Clearly, it scales linearly with \(\mu_0 H/T\) in the low field/high temperature region (\(\mu_0 H/T < 0.2\)), suggesting it may originate from the paramagnetic Er\(^{3+}\) spins at 2a site.

Figure S11 | the \(M(H)\) and the derivative \(dM/dH\) data. a, \(M(H)\) data of \(h\)-ErMnO\(_3\) at various temperatures. b, derivative \(dM/dH\) of the \(M(H)\) data in a. A two-peak feature was observed in the \(dM/dH\) data at various temperatures. As \(T\) decreases, the two peaks get closer and tend to merge to a single peak, i.e. a critical endpoint below 2 K.
Discussion 5  Anomalous magnetoelectric response

The low-temperature magnetic states of \(h\)-ErMnO\(_3\) can be described by a single angle \(\psi = \psi_1 = \psi_2\) (see Fig. S5 for definitions) with \(\psi = 0\) and \(\psi = \pi/2\) corresponding to the B\(_2\) and A\(_2\) phase, respectively. The observed \(B_2 \rightarrow A_2\) transition under an applied magnetic field is the spin re-orientation transition, at which \(\psi\) varies between 0 and \(\pi/2\). The expansion of free energy in powers of \(L_a = L \sin \psi\) compatible with \(P6_3cm\) symmetry of the paramagnetic ferroelectric state is

\[
f = C_{20} L_a^2 + C_{40} L_a^4 + C_{42} L_a^4 H_z^2 + C_{44} L_a^4 H_z^4 + C_{64} L_a^4 H_z^6 + C_{84} L_a^4 H_z^8 + \cdots
\]

where the terms proportional to \(C_{20}\) and \(C_{40}\) describe the 2\(^{nd}\) and 4\(^{th}\)-order magnetic anisotropies, the term \(\propto C_{44}\) describes the weak ferromagnetism in the A\(_2\) phase, \(D_{44}\) is the linear magnetoelectric coupling, etc. The \(P_z\)-dependence is not explicitly shown, since \(P_z\) is invariant under symmetry transformations of the ferroelectric phase (\(P6_3cm\)).

Due to the weak ferromagnetism of the A\(_2\) phase, the angle \(\psi\) is nonzero as soon as \(H_z \neq 0\).

However, the re-orientation largely occurs near \(C_{20} + C_{42} H_z^2 = 0\) and the character of the spin rotation depends on the sign of the 4\(^{th}\)-order anisotropy \(C_{40}\). For \(C_{40} > 0\), the spin re-orientation goes continuously in an extended interval of \(H_z\), while for \(C_{40} < 0\), the angle \(\psi\) abruptly jumps from a small value to \(\pi/2\). Assuming that \(C_{40}\) changes sign at \(\sim 2\) K, we can reproduce the experimentally observed phase diagram using the Landau expansion Eq.(S12), as shown in Fig. S12a where the color represents the value of \(\psi\).
Figure S12 | the simulated $T$-$H$ phase diagrams of the spin re-orientation transition of $h$-ErMnO$_3$ based on phenomenological Landau theory. a, $T$-$H$ phase diagram of the order parameter (the Mn$^{3+}$ spin angle $\psi$). b, $T$-$H$ phase diagram of the magnetoelectric response $\left(\frac{\partial M_z}{\partial E_z}\right)_{E_z=0}$.

In the continuous re-orientation region the angle $\psi$ is very sensitive to applied magnetic and electric fields, which gives rise to the anomaly in the magnetoelectric coefficient,

$$\left(\frac{\partial M_z}{\partial E_z}\right)_{E_z=0} = -\frac{\partial^2 f}{\partial E_z \partial H_z} + \frac{\partial^2 f}{\partial L_{\Lambda_z} \partial E_z} \frac{\partial^2 f}{\partial L_{\Lambda_z} \partial E_z}.$$

(S13)

Here, the first term is proportional to the linear magnetoelectric coupling $D_{11}$, while the second term describes the anomalous response, which is large only in the re-orientation region. As this region shrinks to a point (also the end-point of the first-order transition line) the stiffness $\frac{\partial^2 f}{\partial L_{\Lambda_z}^2}$ becomes small, resulting in a sharp peak in the magnetoelectric susceptibility. The calculated $H_z$-dependence of $\left(\frac{\partial M_z}{\partial E_z}\right)_{E_z=0}$ (see Fig. S12b and Fig. 3h in main text) reproduces well the observed field and temperature dependence of the magnetoelectric response.
Reference