The influence of in-plane ferroelectric crystal orientation on electrical modulation of magnetic properties in Co$_{60}$Fe$_{20}$B$_{20}$/SiO$_2$/(011) xPb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$–(1$-x$)PbTiO$_3$ heterostructures


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(011) cut xPb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$–(1$-x$)PbTiO$_3$ (PMN-PT) ferroelectric crystal is usually used in ferroelectric/ferromagnetic (FE/FM) heterostructures due to its strong voltage-induced anisotropic in-plane strain. (011) PMN-PT crystal includes two in-plane crystal orientations, (010) and (01$-1$), with different piezoelectric strength resulting in anisotropic in-plane strain. Few systematic studies have been conducted to determine the influence of in-plane orientation on magnetoelectric (ME) coupling characteristic in ferroelectric/ferromagnetic composites. In this paper, we report our work to distinguish the contributions of in-plane orientations on electric modulation of magnetic properties. Magneto-optical Kerr effect and propagating spin wave spectroscopy are measured to define the influence of in-plane orientations on electric control of magnetic parameters and spin wave propagation. Magnetoelectric coupling coefficients and frequency modulation coefficients are also calculated. © 2012 American Institute of Physics.

I. INTRODUCTION

Electrical field modulation of magnetic properties has attracted much attention due to its potentials for novel spintronic or magnetoelectric (ME) devices with much lower power consumption and higher speed such as voltage-driven magnetic random access memories, logic circuits, and microwave devices. Much effort has been devoted to achieve room-temperature ME coupling in ferroelectric/ferromagnetic (FE/FM) heterostructures through a strain-induced ME coupling effect across the FE/FM interface. The interface of the FE/FM heterostructures plays a crucial role in determining the ME coupling. Dynamic response (spin waves, SW) of magnetization at RF/microwave frequencies is closely related to the interface of the magnetic films. The techniques usually used to characterize static or dynamic magnetic properties include magnetic force microscopy, magneto-optical Kerr effect (MOKE), ferromagnetic resonance (FMR), Brillouin light scattering, propagating spin wave spectroscopy (PSWS), and so on. Among these, MOKE and FMR techniques are often conducted for the measurements of ME coupling properties in FE/FM composites. However, PSWS technique has not been used before for the study of ME coupling. In FE/FM composites, (011) cut xPb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$–(1$-x$)PbTiO$_3$ (PMN-PT) is often used as the ferroelectric phase due to its large voltage-induced anisotropic in-plane strain (piezoelectricity). For (011) PMN-PT samples, there are two in-plane crystal orientations (100) and (01$-1$), showing anisotropic in-plane strain-voltage properties resulting in orientation dependent ME coupling. However, seldom studies have been performed to directly determine the relation between anisotropic in-plane piezoelectricity and the ME coupling. Here, we report our work to define the influence of in-plane crystal orientation on electrical modulation of magnetic properties in CoFeB/SiO$_2$/(011) PMN-PT heterostructure via MOKE and PSWS measurements.

II. EXPERIMENTAL

Ferroelectric (011) cut PMN-PT (x $\sim$ 0.68) substrates with dimensions of 20 (L) $\times$ 10 (W) $\times$ 0.5 (H) mm$^3$ were purchased and Au films were sputtered onto one side of these non-polarized PMN-PT substrates as the bottom electrodes. To improve the roughness of PMN-PT substrates, SiO$_2$ film with thickness of 190 nm was fabricated onto PMN-PT substrate by plasma enhanced chemical vapour deposition. Then, ferromagnetic Co$_{60}$Fe$_{20}$B$_{20}$ film was sputtered with thickness of 30 nm. Such CoFeB/SiO$_2$/PMN-PT structure was used for the in-plane MOKE measurements. As for the PSWS measurements, the device structure was shown in Fig. 1. Another 190 nm thick SiO$_2$ layer was deposited on the CoFeB film and then a pair of gold coplanar strip-lines (antennae) was then patterned on the top of the SiO$_2$ layer in order to excite at one antenna and detect at the other the spin wave signals. The width of the strip lines was 4.0 $\mu$m and the edge-to-edge separation between both antennae was 8.0 $\mu$m.
The ends of both strip lines were shorted for high efficiency purpose.

For all our electrical field modulation measurements, the external voltage was applied along the film thickness direction. The polarization-electric field (P-E) hysteresis, capacitance-electric field (C-E), and in-plane strain-electric field (s-E) loops were measured in Au/(011) PMN-PT/Au sandwich structure by homemade Sawyer-Tower circuit, HP 4274 A LCR meter and biaxial strain gauge (MicroMeasurements), respectively. HP 8722ES two-port s-parameter vector network analyzer (VNA) was used for the PSWS measurements. Each port of VNA was connected to one antenna in order to generate and detect spin waves. In our PSWS measurements, the direction of the bias magnetic field was applied along the surface of the ferromagnetic film but perpendicular to the propagation direction of the excited spin waves, so surface mode spin waves were detected for the current configuration. To ensure a uniform magnetization in the ferromagnetic film during the measurements, an external bias magnetic field was applied, which was swept from 500 to 0 Oe by step of \( \frac{5.0}{24} \) Oe. At each bias magnetic field, the VNA swept the frequency between 1.0 GHz and 7.5 GHz with input power of 10 dBm (0.1 mW) at one antenna and simultaneously recorded the excited spin waves at the other antenna.

### III. RESULTS AND DISCUSSIONS

Ferroelectric property of (011) PMN-PT substrates was determined by the polarization-electric field hysteresis measurements. Alternating electric field with frequency of 0.1 Hz and various amplitudes of 0.8, 0.4, and 0.2 MV/m, respectively, was applied to Au/(011) PMN-PT/Au sample and P-E hysteresis loops were obtained by integrating the switching current response with respect to the time. From the P-E loops, the remanent polarization \( P_r \) and the coercive field \( E_c \) can be defined. In Fig. 2(a), we compare the P-E loops measured under different electric field amplitudes. With the decrease of amplitude from 0.8 to 0.2 MV/m, P-E loops become rounded indicating unsaturated polarization. From the P-E loop obtained at the field amplitude of 0.8 MV/m, \( P_r \) (18.7 \( \mu \)C/cm\(^2\)) and \( E_c \) (0.158 MV/m) can be determined, corresponding to a coercive voltage \( V_c \) of 79 V for our 0.5 mm thick PMN-PT substrates. C-E loops were also measured by a LCR meter combined with an external source meter. Fig. 2(b) shows the results measured at various frequencies of 10, 40, and 100 kHz. With the increase of the frequency, a slight increase of the capacitance is observed. C-E loops display the typical butterfly shape which is widely observed in inorganic and organic ferroelectrics. However, sharp decrease of the capacitance is also observed when the electric field is adjacent to \( E_c \). This sharp decrease is also reported in our previous work and is the result of the poling of the ferroelectric substrate which causes peaks in the strain change.

The in-plane strain-electric field loops were obtained by mounting a biaxial strain gauge on the top surface of the Au/(011) PMN-PT/Au structure. Each port of VNA was connected to one antenna in order to generate and detect spin waves. In our PSWS measurements, the direction of the bias magnetic field was applied along the surface of the ferromagnetic film but perpendicular to the propagation direction of the excited spin waves, so surface mode spin waves were detected for the current configuration. To ensure a uniform magnetization in the ferromagnetic film during the measurements, an external bias magnetic field was applied, which was swept from 500 to 0 Oe by step of \( \sim 5.0 \) Oe. At each bias magnetic field, the VNA swept the frequency between 1.0 GHz and 7.5 GHz with input power of 10 dBm (0.1 mW) at one antenna and simultaneously recorded the excited spin waves at the other antenna.

![FIG. 1. Device structure for PSWS measurements.](image1)

![FIG. 2. P-E (a) and C-E (b) loops obtained from a (011) PMN-PT substrate.](image2)
magnetic coercivity $H_c$, the remanent magnetization $M_r$, and the anisotropy field $H_{ani}$. During the measurements, the external alternating magnetic field was applied along the in-plane $(01-1)$ and $(100)$ directions to distinguish the contribution of the in-plane orientation on the ME coupling. The results are shown in Figs. 4 and 5. Here, we define two directions along which the applied voltage sweeps. One is the “forward” direction which means the voltage is applied from the positive maximum voltage (400 V) to the negative maximum voltage (~400 V), while the “backward” direction means the voltage is swept from 400 to 0 V.

In Fig. 4, the magnetic field was applied along the in-plane $(01-1)$ direction. Fig. 4(a) shows the change in the normalized Kerr rotation hysteresis (M-H) loops with the applied voltage. The applied voltage causes the conversion of in-plane hard axis into the in-plane easy axis and also increases $H_c$ and $M_r$ when the voltage is applied from 0 to ~400 V. Quantitative analyses of the voltage-induced changes in $H_c$, $M_r$, and $H_{ani}$ are shown in Figs. 4(b)–4(d). In this paper, the anisotropy field is extracted by the second derivative of the M-H loops. All three loops in Figs. 4(b)–4(d) display the inverse butterfly shape following the evolution of the s-E loop obtained along the in-plane $(01-1)$ direction in Fig. 3. The results are well consistent with the experimental observations from Fe$_3$O$_4$(011) PMN-PT structure with magnetic field applied along in-plane $(01-1)$ direction. Note that, in this CoFeB/SiO$_2$(011) PMN-PT/Au structure, due to the voltage drop on the SiO$_2$ layer, the actual voltage applied to the PMN-PT substrate is lower than the apparent voltage shown as the X-axes in Figs. 4(b)–4(d). That is why the observed peak voltage $V_p$ (~130 V), the averaged voltage corresponding to $H_c$, $M_r$, and $H_{ani}$ peaks in Figs. 4(b)–4(d), is much larger than $V_c$ (79 V) of this (011) PMN-PT substrate. Here, we did not attempt to calculate the voltage drop on the PMN-PT substrate, because the change of its dielectric constant with the applied voltage (shown in Fig. 2(b)) makes a quantitative estimation difficult. The maximum changes in $H_c$, $M_r$, and $H_{ani}$ observed in these measurements are 22.93 Oe, 28.4%, and 22.5 Oe, respectively. When the voltage applied to the ferroelectric phase is far away from its coercive voltage, that is, if the ferroelectric phase lies in certain stable polarization state, the changes in $H_c$ and $H_{ani}$ show nearly linear dependence on the applied voltage. For example, in the voltage range between ~60 and 400 V during the forward measurement, both $H_c$ and $H_{ani}$ values linearly decrease with the decrease of the applied voltage. From the change of the anisotropy field, the static “apparent” ME coupling coefficient of 46.2 Oe/kV can be estimated. We call it the

![Fig. 3. In-plane strain measurements by the strain gauge.](image3)

![Fig. 4. MOKE measurement when the magnetic field was applied along the in-plane $(01-1)$ direction. Shown are the normalized Kerr rotation hysteresis loops under different voltages (a) and the changes in $H_c$ (b), $M_r$ (c), and $H_{ani}$ (d) with the applied voltage.](image4)
“apparent” ME coupling coefficient because the actual voltage drop across the ferroelectric phase is lower than the applied voltage. If we assume that the peaks observed in Figs. 4(b)–4(d) are corresponding to the ferroelectric switching (polarization reversal) and do not consider the change in dielectric constant of the ferroelectric phase with the applied voltage, then we can approximately calculate the “real” ME coupling coefficient of 4.92 Oe/C/cm/kV.

In Fig. 5, the magnetic field was applied along the in-plane (100) direction. Fig. 5(a) shows the change in normalized M-H loops with the applied voltage. Different from the experimental observations in Fig. 4(a), here the applied voltage causes the conversion of in-plane easy axis into the in-plane hard axis and also the decrease of both Hc and Mr when the voltage changes from 0 to 400 V. Quantitative analyses of the voltage-induced changes in Hc, Mr, and Hani are shown in Figs. 5(b)–5(d). All three loops in Figs. 5(b)–5(d) show the butterfly shape following the evolution of the s-E loop obtained along the in-plane (100) direction in Fig. 3 and even the sharp decrease of the strain in Fig. 3 is also well repeated in Figs. 5(b)–5(d). Again, the results are well consistent with the experimental observations from Fe3O4/(011) PMN-PT structure with magnetic field along in-plane (100) direction.12 The observed valley voltage Vv, the averaged voltage corresponding to Hc, Mr, and Hani valleys in Figs. 5(b)–5(d), is ~130 V, is larger than the Vc of the PMN-PT substrate. The maximum changes in Hc, Mr, and Hani observed in these measurements are 14.04 Oe, 47.9%, and 11.12 Oe, respectively. Similarly, when the ferroelectric phase lies in certain stable polarization state, the changes in Hc and Hani show nearly linear dependence on the applied voltage. In the voltage range between −60 and 400 V during the forward measurement, the static “apparent” ME coupling coefficient of 19.75 Oe/kV is estimated from the change of Hani, corresponding to a “real” ME coupling coefficient of 1.75 Oe/C/cm/kV. Obviously, from our MOKE measurements, the ME coupling coefficient along the in-plane (01 − 1) direction is about 2.8 times larger than that along (100) direction.

PSWS technique was performed to study the influence of the electric field on the SW propagation in our ME coupling structure. In our PSWS measurements, the direction of the bias magnetic field was applied along the surface of the ferromagnetic film but perpendicular to the propagation direction of the excited spin waves, so surface mode spin waves were detected for the current configuration.14 Fig. 6 shows the typical results of the PSWS measurements in CoFeB/(011) PMN-PT heterostructure. The S12 response map recorded by the VNA is plotted in Fig. 6(a) as a function of both bias magnetic field and excitation frequency. Strong spin wave features are well visualized and the SW frequency increases with the increase of external magnetic field. According to the theory of surface mode spin waves, the SW frequency f is determined by

\[
f^2 = \left( \frac{\gamma}{2\pi} \right)^2 \left[ (H_o + H_{ani})(H_o + H_{ani} + M) + \frac{M^2}{4} (1 - e^{-2kd}) \right],
\]

where \(H_o\) is the external bias magnetic field, \(M\) the saturation magnetization, \(k\) the in-plane wave vector, \(d\) the thickness of the ferromagnetic film, and \(\gamma\) the gyromagnetic ratio. By fitting the experimental spin wave curve to Eq. (1), the values of saturation magnetization and ferromagnetic film thickness...
can be extracted\(^8\). Upon the application of the external voltage across the ferroelectric phase, the anisotropy field \(H_{\text{an}}\) of the ferromagnetic phase can be changed due to the strain coupling at FE/FM interface. From Eq. (1), the SW frequency changes with the anisotropy field, as is also shown in Fig. 6(b). An external voltage was applied to the ferroelectric phase resulting in the change of the polarization state and then the strain of the ferroelectric phase. At each polarization state, \(S_{12}\) response map, similar to Fig. 6(a), was recorded by VNA as a function of the bias magnetic field and the excitation frequency, from which the voltage-dependent SW frequency and the voltage-dependent effective magnetic field could be defined. Fig. 6(a) indicates the voltage-dependent SW frequency at the bias magnetic field of 300 Oe. During the forward measurement, (011) PMN-PT substrate was firstly positively polarized by +200 V for 5 min, then the external voltage decreased by voltage step of 10 V down to −200 V. The SW frequency at each polarization, corresponding to an external bias magnetic field of 300 Oe, was extracted from the \(S_{12}\) response map. Before polarization reversal which occurs at about −70 V in Fig. 6(b), the SW frequency decreases linearly with the decrease of the applied voltage. Then, the large enough negative voltage (−70 V) induces the polarization reversal and on the contrary the SW frequency increases with the further decrease of the applied voltage down to −200 V, resulting in the occurrence of a valley in the forward voltage-dependence frequency curve. The same voltage-dependent change of SW frequency is also observed during the backward measurement. The combination of both frequency displays the butterfly shape. Note that we also observe the sharp change of the SW frequency during ferroelectric switching, which is highlighted by circles in Fig. 6(b). The butterfly shape in Fig. 6(b) well repeats the shape of inverse s-E loop observed along the (100) direction in Fig. 3. From Fig. 6(b), the averaged frequency modulation in the linear region was about 72 MHz cm/kV in this CoFeB/(011) PMN-PT heterostructure.

PSWS measurements were performed in CoFeB/SiO\(_2\)/(011) PMN-PT heterostructure to determine the influence of in-plane crystal orientation on SW propagation. In the measurements, the magnetic field was applied along the in-plane \(\langle 100 \rangle\) (or \(\langle 01 \rangle \)) direction while spin waves were detected along the \(\langle 01 \rangle \) (or \(\langle 10 \rangle \)) direction. Both SW frequency vs. voltage curve and effective magnetic field vs. voltage curve were determined when the applied voltage decreased from 200 to −200 V by voltage step of 10 V (forward process) and plotted in Figs. 7(a) and 7(b). Large fluctuation observed in both blue curves under the condition of \(H_z//\langle 100 \rangle\) and \(SW//\langle 01 \rangle\) (\(H_{\text{ex}}\): external magnetic field) is due to the strong coupling between the spin waves and the electromagnetic waves which makes it hard to determine the real minimum value in \(S_{12}\) response map. However, both curves are still clear enough to show their dependence on the applied voltage.

As for voltage dependence of the SW frequency in Fig. 7(a), we take as example the SW frequency corresponding to the external magnetic field of 150 Oe.

(1) Condition: \(H_z//\langle 01 \rangle\) and \(SW//\langle 10 \rangle\) (the black curve in Fig. 7(a)). In positively polarized state between 200 and −120 V, SW frequency decreases with the decrease of the applied voltage; at about −120 V, ferroelectric switching occurs and then the ferroelectric phase becomes negatively polarized resulting in the increase of the SW frequency with further decrease of the applied voltage from −120 to −200 V. The whole frequency-voltage curve follows the shape of the inverse s-E butterfly loop obtained along in-plane \(\langle 100 \rangle\) direction in Fig. 3. In this measurement, the maximum frequency change is about 0.557 GHz occurring after polarization reversal. In the positively polarized state of the ferroelectric phase, a frequency modulation of 0.942 MHz/V is observed. Similarly, if we assume that the valley from the black curve in Fig. 7(a) is corresponding to the ferroelectric switching and do not consider the change in dielectric constant of the ferroelectric phase with the applied voltage, then we can approximately calculate the “real” frequency modulation of 71.6 MHz cm/kV. This value is well consistent with that (72 MHz cm/kV) obtained from CoFeB/(011) PMN-PT structure in Fig. 6(b), which also indicates that the inset of SiO\(_2\) between CoFeB layer and PMN-PT substrate does not result in obvious degradation of the frequency modulation characteristic.

(2) Condition: \(H_z//\langle 10 \rangle\) and \(SW//\langle 01 \rangle\) (the blue curve in Fig. 7(a)). In positively polarized state between 200 and −110 V, SW frequency increases with the decrease of the applied voltage, opposite to the trend shown by the black curve; at about −110 V, ferroelectric switching occurs and then the ferroelectric phase changes to...
negatively polarized state resulting in the decrease of the SW frequency with further decrease of the applied voltage from −120 to −180 V; finally, SW frequency increases again with the voltage decrease from −180 to −200 V. The maximum frequency change of 0.35 GHz occurs during ferroelectric switching. The whole blue frequency-voltage curve follows the shape of the forward part of the s-E loop obtained along in-plane \((01 \_1)\) direction in Fig. 3. In the linear region between −50 and 130 V, a frequency modulation of 1.07 MHz\/V is observed. Similarly, we can approximately calculate the “real” frequency modulation of 74.8 MHz cm\/kV. This value is nearly the same as that (71.6 MHz cm\/kV) obtained from the black curve in Fig. 7(a).

As for voltage dependence of the effective magnetic field \(H_{\text{eff}}\) in Fig. 7(b), we take as example the \(H_{\text{eff}}\) corresponding to SW frequency of 5.0 GHz.

(1) Condition: \(H_{\text{ac}}/(01 \_1)\) and \(SW//\langle 100\rangle\) (the black curve in Fig. 7(b)). In positively polarized state between 200 and −120 V, \(H_{\text{eff}}\) increases with the decrease of the applied voltage; at about −120 V, ferroelectric switching occurs and then the ferroelectric phase changes to negatively polarized state resulting in the decrease of \(H_{\text{eff}}\) with further decrease of the applied voltage from −120 to −200 V. The whole \(H_{\text{eff}}\)-voltage curve follows the shape of the s-E butterfly loop obtained along in-plane \((01 \_1)\) direction in Fig. 3. The maximum \(H_{\text{eff}}\) change is about 66.7 Oe after polarization reversal. In the linear region of the positively polarized state between 200 and −80 V, a \(H_{\text{eff}}\) modulation of 144 Oe\/kV is observed, corresponding to a “real” ME coupling coefficient of 10.96 Oe cm\/kV.

(2) Condition: \(H_{\text{ac}}/(100)\) and \(SW//(01 \_1)\) (the blue curve in Fig. 7(b)). In positively polarized state between 200 and −120 V, \(H_{\text{eff}}\) decreases with the decrease of the applied voltage; at about −120 V, ferroelectric switching occurs and then the ferroelectric phase becomes negatively polarized resulting in the increase of \(H_{\text{eff}}\) with further decrease of the applied voltage from −120 to −160 V; finally, \(H_{\text{eff}}\) decreases again with the decrease of the voltage down to −200 V. The whole blue \(H_{\text{eff}}\)-voltage curve repeats the shape of inverse s-E loop obtained along in-plane \((01 \_1)\) direction in Fig. 3. In the linear region of the positively polarized state between 200 and −80 V, a \(H_{\text{eff}}\) modulation of 76.9 Oe\/kV is observed, corresponding to a “real” ME coupling coefficient of 5.84 Oe cm\/kV.

The voltage modulation curves of SW frequency (Fig. 7(a)) and effective magnetic field (Fig. 7(b)) during the propagation of spin waves along \((01 \_1)\) (or \(\langle 100\rangle\)) direction show the same shapes with the Hain-voltage curve (Figs. 4(d) and 5(d)) and the strain-electrical field curve (Fig. 3) along \(\langle 01 \_1\rangle\) (or \(\langle 100\rangle\)) direction. It seems that these results imply it is the strain along the SW propagation direction, rather than along the magnetic field direction, that determines the electric modulation of SW propagation, at least the shape of SW modulation curves.

By MOKE and PSWS measurements, we have determined the ME coupling coefficients and the spin wave frequency modulation. Here, we will give some brief discussions on these results.

The ME coupling coefficient calculated from the PSWS measurements is much larger than that from MOKE measurements. For example, consider the situation when the magnetic field is along in-plane \((01 \_1)\) direction in CoFeB/SiO\(_2\)/(011) PMN-PT structure. The ME coupling coefficient is 10.96 and 4.92 Oe cm\/kV for PSWS and MOKE measurements, respectively. This may be due to the different methods used to define the ME coupling coefficient. In the MOKE measurements, ME coupling is quantified by the anisotropy field which is determined by the second derivative of the M-H loops, while, in the PSWS measurements, ME coupling is defined by the so-called effective magnetic field corresponding to certain SW frequency. However, all ME coupling coefficients obtained in our CoFeB/SiO\(_2\)/(011) PMN-PT heterostructure are much lower than the reported large
coefficient of 67 Oe cm/kV observed in Fe₃O₄/PZN-PT heterostructures. Besides the different techniques used to calculate the ME coupling coefficients, the weak ME coupling may be also due to the unoptimized device configuration and the relatively lower piezoelectricity in PMN-PT substrates.

In our PSWS measurements, we observe SW frequency modulation as large as 72 and 74.8 MHz cm/kV for different SW propagation direction in both CoFeB/SiO₂/(011) PMN-PT and CoFeB/(011) PMN-PT heterostructures. Both values are much larger than some results from other FE/FM heterostructures. For example, in PZT(0.5 mm)/(111) YIG (0.11 mm) heterostructure frequency modulation of 2.4 MHz cm/kV was reported; in another PZT (0.5 mm)/(111) YIG (15 μm) heterostructure with thinner yttrium iron garnet (YIG) thickness, slightly larger frequency modulation of 2.62 MHz cm/kV was observed; and in (001) PMN-PT (0.5 mm)/(111) YIG (15 μm) structure frequency modulation of 6.6 MHz cm/kV was observed. The large frequency modulation in our work should be attributed to the nanoscale ferromagnetic film which tends to be influenced by the strain coupling at FE/FM interface.

IV. CONCLUSIONS

In summary, via MOKE and PSWS measurements we determined the influence of the in-plane crystal orientation on both static and dynamic ME coupling characteristics. Experimental observations indicate that in in-plane MOKE measurements, the in-plane strain along the magnetic field direction determines the ME coupling characteristic; while in PSWS measurements of the surface spin waves, SW modulation curves show the same shapes with the corresponding strain-electric field curves and also the Hₑᵥₑ-voltage curves. It seems imply that it is the strain along the detection direction that shows the obvious influence on the electric control of SW propagation, at least the shape of the SW modulation curves.

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