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Tunable Short-Wavelength Spin-Wave Emission and Confinement in Anisotropy-Modulated Multiferroic Heterostructures

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We report on the generation and confinement of short-wavelength spin waves in a continuous film with periodically modulated magnetic anisotropy. The concept, which is demonstrated for strain-coupled $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{BaTiO}_3$ heterostructures, relies on abrupt rotation of magnetic anisotropy at the boundaries of magnetic stripe domains. In combination with an external bias field, this modulation of magnetic anisotropy produces a lateral variation of the effective magnetic field, leading to local spin-wave excitation when irradiated by a microwave magnetic field. In domains with small effective field, spin waves are perfectly confined by the spin gap in neighboring domains. In contrast, standing spin waves in domains with large effective field radiate into neighboring domains. Using micromagnetic simulation, we show that the wavelength of emitted spin waves is tunable from a few micrometers down to about 100 nm by rotation of the bias field. Importantly, the orientation of the wave front remains fixed. We also demonstrate that dynamic fluctuations of the effective magnetic field produce exchange-dominated spin waves at single-anisotropy boundaries. The multiferroic heterostructures presented here enable the use of global excitation fields from a microwave antenna to emit tunable spin waves from a nanometer-wide line source at well-defined locations of a continuous ferromagnetic film.

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I. INTRODUCTION

Excitation of short-wavelength spin waves from a precise location is essential for the downscaling of magnonic devices and the realization of spin-wave-based computing [1–3]. Several methods have been explored in recent years. Among them are spin-wave injection from spin-torque nano-oscillators [4–7] and all-optical excitation using focused laser beams [8–10]. The wavelength of emitted spin waves from these pointlike sources is roughly twice the nano-oscillator or laser spot size. Topological defects in magnetic films such as vortices and domain walls provide another means of local spin-wave emission [11–13]. Pinned magnetic domain walls in magnetic nanowires that are brought into oscillation by a microwave spin-polarized current, for instance, allow for monochromatic spin-wave emission up to high frequency [12]. The wavelength of spin waves that are emitted by oscillating noncollinear spin textures decreases with frequency. The aforementioned generation schemes either rely on electric current or optical excitation inside the spin-wave-carrying layer, which can lead to unwanted heating and lateral variations of spin-wave dispersions. Alternatives based on wavelength conversions

in the vicinity of microwave antennas are also available. Examples include tapered waveguides [14], waveguides coupled to a magnetic antenna [15], grating couplers [16,17], isolated antidots [18,19], and nanowire or nanodisk microwave-to-spin-wave transducers [20,21]. Attaining short-wavelength spin-wave emission with any of these approaches requires patterning of a ferromagnetic layer at the nanoscale.

Here, we report on the confinement and emission of spin waves in multiferroic heterostructures consisting of a structurally continuous $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film on a ferroelectric BaTiO_3 substrate with ferroelastic stripe domains (Fig. 1). Strain transfer at the interface of this hybrid structure causes imprinting of a ferromagnetic stripe pattern that is characterized by 90° rotations of uniaxial magnetic anisotropy at ferroelectric boundaries [22,23]. In combination with an external bias field, the regular modulations of magnetic anisotropy divide the system into alternating stripes with dissimilar effective magnetic field. Since the ferroelectric boundaries are perfectly straight and only a few nanometers wide [24,25], the effective magnetic field changes abruptly at parallel lines within the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film. Using broadband spin-wave spectroscopy and micromagnetic simulations, we demonstrate excitation of confined spin-wave modes in stripes with small effective magnetic field. At

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FIG. 1. Illustration of a strain-coupled $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{BaTiO}_3$ sample that allows for the confinement and emission of short-wavelength spin waves without nanopatterning. The arrows and rectangles in the BaTiO_3 layer indicate the orientation of ferroelectric polarization and lattice tetragonality. The double-headed arrows in $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ depict the orientation of a strain-induced uniaxial magnetic anisotropy axis (UMA). If a magnetic field is applied along the UMA of one of the domain types (light gray stripes in this illustration), the effective magnetic field and spin-wave dispersion relation change abruptly at the domain boundaries. As a consequence, a microwave magnetic field excites first- and higher-order standing spin waves in stripe domains with small effective magnetic field (dark gray stripes with UMA perpendicular to H_{ext}). Excitation of standing spin-wave modes in domains with large effective field (light gray stripes with UMA parallel to H_{ext}) results in the emission of short-wavelength spin waves into neighboring domains.

higher frequency, standing spin waves are also excited in stripes with large effective field. Our simulations show that this excitation causes emission of spin waves into neighboring domains. The wavelength of the emitted spin waves is tunable from a few micrometers to about 100 nm by reorientation of an external bias field. Compared to methods that rely on a modification of the effective magnetic field by nanostructuring [14,16–21], the presented multiferroic system does not require lithography. Finally, we show that dynamic fluctuations of the effective magnetic field at a single-anisotropy boundary suffices for broadband spin-wave emission. With increasing excitation frequency, the character of the emitted spin waves changes from magneto-static to exchange dominated. Magnetic anisotropy boundaries under global excitation conditions can, thus, be used as tunable sources of spin waves with ultrashort wavelength comparable to soft x rays [21].

The results presented here differentiate from spin-wave emission from a pinned magnetic domain wall in multiferroic heterostructures, as discussed in Ref. [12]. In the latter study, an intense ac spin-polarized current drives a magnetic domain wall into oscillations via the spin-transfer-torque effect. Practical realizations of such a current-actuated spin-wave source requires patterning of the ferromagnetic film into a nanowire. Moreover, the use

of intense electric currents can cause unwanted heating. We also note that the efficiency of the spin-transfer-torque effect varies with the angle between the directions of magnetization in neighboring domains. As a result, an external magnetic bias field substantially reduces spin-wave emission when a spin-polarized current is used. In contrast, regular modulations of magnetic anisotropy rather than pinned magnetic domain walls determine spin-wave emission and confinement by global microwave magnetic fields. Here, an external magnetic bias field is required to produce stripe domains with different effective fields. If a microwave antenna is used, spin waves are still excited from the anisotropy boundaries when a saturating bias field erases all magnetic domain walls. Consequently, this excitation mechanism enables active tailoring of the spin-wave wavelength by an external magnetic field, which is not possible with domain walls as they will be erased.

II. SAMPLE PREPARATION, EXPERIMENTAL DETAILS, AND SIMULATION PARAMETERS

A schematic illustration of the sample is depicted in Fig. 1. It consists of a 0.5-mm-thick ferroelectric BaTiO_3 substrate with regular stripe domains and an overlaying 50-nm-thick $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film. The ferroelectric polarization is oriented in plane along the elongated lattice parameter of the tetragonal unit cell, and it abruptly rotates by 90° at domain boundaries. Because of strain coupling, a periodically modulated magnetic anisotropy is induced in the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film via inverse magnetostriction. As a result, the ferromagnetic and ferroelectric domain patterns are fully correlated, and the magnetic domain walls are firmly pinned onto their ferroelectric counterpart. The uniaxial magnetic anisotropy and ferroelectric polarization of the multiferroic heterostructure are collinear, making angles of $\pm 45^\circ$ with respect to the domain boundaries. The uniaxial magnetic anisotropy axis, i.e., the preferred direction of magnetization in the stripe domains, are hereafter labeled as UMA.

To attain full ferromagnetic ferroelectric domain correlations, the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film is grown by magnetron sputtering at an elevated temperature of 300°C . At this temperature, the BaTiO_3 substrate is paraelectric, and its crystal structure is cubic. The ferroelectric and ferromagnetic stripe domains are formed during postdeposition cooling through the paraelectric-to-ferroelectric phase transition ($T_C \approx 120^\circ\text{C}$). At room temperature, a 5-nm Au capping layer is added to prevent oxidation.

The magnetostatic properties of the sample are characterized by vibrating sample magnetometry (VSM) and magneto-optical Kerr microscopy. The latter technique is used to image the ferromagnetic domain structure and record local hysteresis curves on single stripe domains as a function of magnetic field angle (Fig. 2). Spin-wave excitations in the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film are measured using broadband spin-wave

FIG. 2. (a) Kerr microscopy image of the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{BaTiO}_3$ sample in zero magnetic field. The arrows in the domains indicate the direction of magnetization. (b) Polar plot of the remanent magnetization in two neighboring stripe domains as a function of magnetic field angle θ . The data are obtained by analyzing Kerr microscopy images of the domains separately. (c) Magnetic hysteresis curves of two neighboring stripe domains. The magnetic field is oriented along the UMA of the narrow domains, i.e., $\theta = 135^\circ$. The blue dashed line indicates the magnetic anisotropy field.

spectroscopy [26]. In the experimental setup, the sample is placed face down onto a coplanar waveguide (CPW) with a 20- μm -wide signal line, as illustrated in Fig. 3(a). The CPW is connected to a vector network analyzer and produces a long-wavelength microwave field (H_{rf}) with a main excitation at $|k| = 0.096 \text{ rad}/\mu\text{m}$ [27]. In all measurements, H_{rf} is oriented perpendicular to the stripe domains of the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{BaTiO}_3$ sample. A quadrupole electromagnet is used to provide an external bias field (H_{ext}) along different in-plane directions. We define the angle θ of the bias field

with respect to the domain boundaries in the BaTiO_3 substrate [Figs. 2(a) and 3(a)].

Micromagnetic simulations are performed in MuMax3 [28]. The ferromagnetic stripe domains are discretized using finite-difference cells with a size of $3.05 \times 3.05 \times 50 \text{ nm}^3$. Two-dimensional periodic boundary conditions are applied to mimic an infinite $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film. Regular modulations of strain-induced magnetic anisotropy are introduced by abrupt rotation of the UMA at the domain boundaries. In the simulations, spatially uniform Gaussian field pulses and

FIG. 3. (a) Broadband spin-wave spectroscopy measurement geometry. We note that the CPW and sample are not plotted to scale; DW, domain wall. (b) Gray-scale plot of the field-dependent transmission signal measured for $\theta = 135^\circ$. The blue dashed line indicates the magnetic anisotropy field. (c) Angular dependence of spin-wave excitations in $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{BaTiO}_3$ at a constant magnetic field of 60 mT. In addition to first-order standing spin waves in both stripe domains (two main branches), we also measure higher-order spin-wave modes. Higher-order modes in the broad domains are visible for $135^\circ \lesssim \theta \lesssim 170^\circ$ as indicated by the labels. For clarity, we show frequency scans for $\theta = 147^\circ$ and $\theta = 159^\circ$ in (d) and (e). The feature at 11.5 GHz that is indicated by a red arrow in (d) and (e) and the corresponding white horizontal line in (b) and (c) are caused by the subtraction of a reference measurement. Higher-order modes in the narrow domains are visible in (c) for $10^\circ \lesssim \theta \lesssim 45^\circ$. The eigenfrequencies of the confined spin-wave modes are slightly higher for the narrow domains. (f) Micromagnetic simulation of the broadband spin-wave spectrum as a function of magnetic field angle. In the simulation, alternating stripe domains with a width of 5 and 7.5 μm are assumed. The simulation confirms the excitation of confined spin-wave modes and the dependence of eigenfrequencies on stripe-domain width.

global sinusoidal ac magnetic fields are used to excite spin waves.

III. MAGNETOSTATIC PROPERTIES AND SPIN-WAVE CONFINEMENT

Figure 2(a) shows a Kerr microscopy image of the sample at zero magnetic field. The sample consists of stripe domains with an alternating width of $5 \pm 1.5 \mu\text{m}$ and $7.5 \pm 1.5 \mu\text{m}$. In remanence, the magnetization of each domain aligns along its UMA. The 90° modulation of magnetic anisotropy is confirmed by the angular dependence of remanent magnetization [polar plots in Fig. 2(b)]. If the external magnetic field is applied along the UMA of the narrow stripe domains ($\theta = 135^\circ$), a square local hysteresis curve is obtained, while the hysteresis curve of neighboring stripes is closed [Fig. 2(c)]. The strength of uniaxial magnetic anisotropy (K_u) is derived from $K_u = \mu_0 H_{\text{an}} M_s / 2$, where ($\mu_0 H_{\text{an}}$) is the anisotropy field of the hard-axis hysteresis curve. Using a saturation magnetization of $M_s = 1.15 \times 10^6 \text{ A/m}$ (from VSM), we find $K_u = 1.4 \times 10^4 \text{ J/m}^3$.

Figure 3(b) shows a broadband spin-wave spectrum for $\theta = 135^\circ$, i.e., with H_{ext} oriented along the UMA of the narrow stripe domains. Two prominent branches with different field dependences are obtained. The branch with two characteristic minima is produced by a spin-wave mode in the broad stripe domains. The magnetic anisotropy field that is derived from the field position of the frequency minima (approximately 25 mT) corresponds closely to the Kerr microscopy data of Fig. 2(c). Spin-wave excitation in domains with H_{ext} parallel to the UMA, i.e., the narrow domains, is responsible for the branch at high frequencies. The frequency of this mode increases monotonically with magnetic bias field. At small H_{ext} , coherent magnetization rotation and abrupt magnetic switching in the two types of stripe domains alter the angle between H_{rf} and the magnetization direction and, thereby, the intensity of excited spin-wave modes. In the remainder of this article, we focus on a $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film wherein the magnetization is aligned along a strong external bias field ($\mu_0 H_{\text{ext}} = 60 \text{ mT}$). The angular dependence of the broadband spin-wave spectrum for this nearly uniform magnetization state is shown in Fig. 3(c). The frequencies of the two main branches oscillate and become degenerate when H_{ext} is oriented either parallel or perpendicular to the domain boundaries ($\theta = 0^\circ$ and 90°). We also encounter a set of spin-wave modes that exhibit intensities smaller than the two main modes [see, also, Figs. 3(d) and 3(e)]. Their overall field dependences follow the angular variation of one of the main modes. From this, we conclude that the additional resonances correspond to higher-order standing spin waves in the stripe domains. We note that the CPW in our experiment mainly excites spin waves with a wave vector of $|k| = 0.096 \text{ rad}/\mu\text{m}$ in an unpatterned ferromagnetic film. The corresponding wavelength amounts to about $65 \mu\text{m}$, i.e., about 10 times the individual stripe-domain width. Nonuniformity in the

excitation field does not, therefore, affect spin-wave confinement much.

To further elucidate the origin of spin-wave modes in our hybrid system, micromagnetic simulations are performed. The simulation region consists of four stripe domains with an alternating width of 5 and $7.5 \mu\text{m}$, and periodic boundary conditions are applied in both the x and y directions. The experimental results of $K_u = 1.4 \times 10^4 \text{ J/m}^3$ and $M_s = 1.15 \times 10^6 \text{ A/m}$, together with an exchange constant of $K_{\text{ex}} = 2.1 \times 10^{-11} \text{ J/m}$ and a damping parameter of $\alpha = 0.005$ are used as inputs. Moreover, an external bias field of 60 mT is applied at a fixed angle. After obtaining the ground state of the system, it is excited by a spatially uniform 1-mT Gaussian field pulse. The magnetic field pulse is oriented in plane and perpendicular to the domain boundaries. The fundamental resonances are located by Fourier transforming the z component of magnetization after the excitation pulse. This methodology is repeated for different angles of the magnetic bias field ranging from 0° to 180° in 1.5° steps. The simulation result in Fig. 3(f) is in good agreement with the experimental data of Fig. 3(c). A comparison with experimental data suggests that standing spin waves up to ninth order are excited in stripe domains where the effective field is smaller than that of neighboring domains. In contrast, only the first-order spin-wave mode is experimentally resolved for stripes with large effective field. The slight asymmetry in the spin-wave spectra is caused by the difference in stripe-domain width. The eigenfrequencies of confined spin-wave modes in the $5\text{-}\mu\text{m}$ -wide domains are higher than that of the corresponding modes in the $7.5\text{-}\mu\text{m}$ -wide domains. This upward frequency shift is explained by the positive slope of the spin-wave dispersion curves [Fig. 4(b)].

Micromagnetic simulations of standing spin-wave profiles are obtained by continuous pumping with a 0.1-mT global in-plane sinusoidal ac magnetic field until a steady state is achieved. Figure 4 shows the results for $\theta = 135^\circ$, i.e., with $H_{\text{ext}} = 60 \text{ mT}$ perpendicular to the UMA of the $7.5\text{-}\mu\text{m}$ -wide domains. For this field orientation, the difference in effective magnetic field between neighboring domains is maximized, and the direction of magnetization varies by only approximately 0.2° [Fig. 4(a)]. The abrupt changes in effective field are caused by instant 90° rotations of the UMA at domain boundaries. For each domain type, the dispersion relation $f(k)$ is calculated using the model by Kalinikos and Slavin [29], omitting the finite width of the stripe domains. Dispersion relations for domains with small and large effective magnetic field are shown in Fig. 4(b). We find that dispersion relations in the two different domains are well separated on the frequency axis. The effect of confinement is studied via micromagnetic simulations. Between the domain boundaries, standing spin waves are found to exist. In the following, we consider spin waves with $k = n\pi/w$, where n takes odd integer numbers, and w is the width of the domains. We focus on odd n as

FIG. 4. (a) Simulated effective magnetic field and magnetization direction in a $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film for an external bias field of 60 mT and $\theta = 135^\circ$. We consider alternating stripe domains with $w = 5 \mu\text{m}$ and $w = 7.5 \mu\text{m}$. The effective field is smaller for the broad domains where the external bias field is oriented perpendicular to the UMA. (b) Calculated dispersion relations for both stripe domains. We assume the wave vector k to be perpendicular to the domain walls. The colored dots on the black line designate standing spin-wave modes in domains with small effective field ($w = 7.5 \mu\text{m}$). The dots on the red dispersion curve indicate first- and third-order standing spin-wave modes in domains with large effective field ($w = 5 \mu\text{m}$). (c)–(f) Simulated spin-wave profiles of the first-, third-, fifth-, and seventh-order modes formed in domains with small effective field. Parameter m_z indicates the normalized out-of-plane magnetization component ($m_z = M_z/M_s$). For clarity, we show four domains.

only odd modes are excited in simulations and experiments due to the symmetry of the spatially uniform magnetic excitation field. Simulated spin-wave profiles of the first, third, fifth, and seventh confined modes in the $7.5\text{-}\mu\text{m}$ -wide domains with small effective magnetic field are shown in Figs. 4(c)–4(f). Thus, the excitation of confined spin waves in structurally continuous $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ is explained by an abrupt change in effective magnetic field at perfectly straight anisotropy boundaries. Similar to spin-wave confinement by dipolar magnetic fields in nanowires [30,31] or magnetic domain walls [32], standing spin waves form between two boundaries when the accumulated phase difference equals an integer multiple of π . For the perfectly confined case where the effective field in the excited stripe is smaller than that of neighboring domains, the wave vector becomes imaginary at the stripe boundary due to an

abrupt shift in the dispersion relation. Since no modes exist in the neighboring domains, propagation of spin waves into these areas is forbidden, and the z component of magnetization decays quickly. The absence of propagating modes leads to quantization of higher-order spin-wave modes until real-valued modes exist in the dispersion branch of neighboring domains and the confinement strength is reduced.

IV. SPIN-WAVE EMISSION

Spin-wave excitation in domains with large effective field is less confined and leads to the emission of short-wavelength spin waves into neighboring domains (Fig. 5). This phenomenon is illustrated by additional micromagnetic simulations performed on a continuous magnetic film with 7.5- and $22.5\text{-}\mu\text{m}$ -wide stripe domains. An external bias field of 60 mT is oriented parallel to the UMA of the $7.5\text{-}\mu\text{m}$ -wide domain, creating a large effective field. Intentionally, the neighboring domains are broad to avoid complex interference patterns of propagating waves in simulation geometries with periodic boundary conditions. The simulated effective magnetic field and magnetization configuration are shown in Fig. 5(a). A first-order standing spin wave is excited in the $7.5\text{-}\mu\text{m}$ -wide domain using a spatially uniform 0.1-mT sinusoidal ac magnetic field. The time evolution of this process is illustrated in Fig. 5(b). In addition to the buildup of a confined spin wave in the $7.5\text{-}\mu\text{m}$ -wide domain, a propagating wave front with considerable amplitude but shorter wavelength develops in the neighboring domains. This mode conversion mechanism is explained by the downward frequency shift of the dispersion relation at the domain boundary [Fig. 5(c)]. Because of the lateral variation of spin-wave dispersion relations $f(k)$, a short-wavelength mode exists in domains with small effective field at the excitation frequency of a standing spin-wave mode in domains with large effective field. This conversion process is illustrated by the arrow in Fig. 5(c). Domains with large effective field, thus, act as a local spin-wave source. Since the confined and propagating modes have identical eigenfrequency, it is not possible to resolve the launching of short-wavelength spin waves in the broadband spectra of Fig. 3.

The wavelength of emitted spin waves can be tuned by rotation of the external bias field, as shown in Fig. 5(d). At $\theta = 45^\circ$, the spin waves have a wavelength of about 1600 nm. Rotation of H_{ext} away from the UMA of the $7.5\text{-}\mu\text{m}$ -wide stripe domain either increases or decreases the wavelength of propagating spin waves, depending on the rotation direction. Directing the external bias field more perpendicularly to the stripe domains, i.e., an increase of θ , leads to a significant wavelength reduction. As an example, the profile of emitted spin waves for $\theta = 72^\circ$ is shown in the inset of Fig. 5(d). The decrease of wavelength is explained by a flattening of the dispersion curves when the angle between the wave vector of propagating spin waves and the direction of magnetization is reduced [29]. In

FIG. 5. (a) Effective magnetic field and magnetization direction for a 7.5- μm -wide stripe domain with large effective field (H_{ext} parallel to the UMA) and 22.5- μm -wide neighboring domains with small effective field (H_{ext} perpendicular to the UMA). In this simulation, $\mu_0 H_{\text{ext}} = 60$ mT and $\theta = 45^\circ$. (b) Formation of standing and propagating spin waves as a function of time after the onset of ac field excitation. T_0 corresponds to the period of the excitation signal. (c) Illustration of wavelength conversion at an abrupt boundary between two domains with different effective magnetic field. The dispersion curves are calculated for $\mu_0 H_{\text{ext}} = 60$ mT and $\theta = 45^\circ$. (d) Wavelength and frequency of emitted spin waves as a function of bias field angle. The inset shows a spin-wave profile for $\theta = 72^\circ$. (e), (f) Profiles of emitted spin waves from a first-order confined mode for different angles of $\mu_0 H_{\text{ext}} = 60$ mT. (g), (h) Profiles of emitted spin waves from a third-order standing spin-wave mode. We note that the length scale of the horizontal axis in (f) is different from (e) and (g).

addition to wavelength tuning, rotation of H_{ext} also shifts the excitation frequency via a change of effective magnetic field. Because of the infinite length of the stripe domains, the wave fronts of emitted spin waves are parallel to the domain boundaries [12], as illustrated by the two-dimensional magnetization profiles in Figs. 5(e) and 5(f). Rotation of the external bias field, thus, actively tunes the

wavelength of spin waves down to the nanometer scale without altering their propagation direction.

We also note that the excitation of higher-order standing spin-wave modes triggers the emission of short-wavelength spin waves. An example for the third-order mode is shown in Figs. 5(g) and 5(h). In these simulations, a $\mu_0 H_{\text{ext}} = 60$ mT magnetic field is oriented at $\theta = 45^\circ$, which is identical to the field geometry in Fig. 5(e).

Finally, we assess the possibility of spin-wave excitation from a single-anisotropy boundary using a global microwave field. Davies and Kruglyak [19] have shown that it is possible to emit propagating spin waves from an isolated straight edge of a semi-infinite magnetic film. In their geometry, a large nonuniformity in the dynamic demagnetization field triggered the emission of magneto-static spin waves with a wavelength of several hundred nanometers. In their case, the distribution of the static demagnetizing field across the width of the stripe was uniform. They argued that the dynamic demagnetization effect led to a pinning of spins at the edge that allowed for the excitation of spin waves with a finite wave vector. The emission of spin waves was unidirectional into the thin film. In our anisotropy-modulated system, the effective magnetic field varies on a nanometer length scale between two uniform levels under quasistatic conditions. Strikingly, this nanoscale inhomogeneity allows one to induce bidirectional emission of short-wavelength spin waves using a global microwave field (Fig. 6). Following our micromagnetic simulations, the microwave field induces a forced and nonresonant spin precession on both sides of the magnetic anisotropy boundary. As the effective fields are different on the two sides, the spin-precessional amplitudes are slightly different, and a time-dependent (nonzero) divergence in magnetization M is induced locally at the magnetic anisotropy boundary. This inhomogeneity launches spin waves with finite wave vector k . The mechanism allows one to emit spin waves in two directions, which is not the case for the spin waves emitted via surface charges in Ref. [19]. Using identical simulation parameters as in Fig. 5, we find that the character of the spin waves emitted from the magnetic anisotropy boundary changes gradually from magnetostatic to exchange-dominated with increasing frequency. This change is illustrated by the upturn in the dispersion curves of Fig. 6(d) for large k . Considering the two different levels of the quasistatic effective field for regions with H_{ext} parallel to the UMA and H_{ext} perpendicular to the UMA, the dispersion relations are different for left- and right-propagating spin waves. We note that a surface localization effect might modify the dispersion relation when the in-plane wavelength becomes smaller than the thickness of the ferromagnetic film [33]. This effect, which is relevant only for the very right-hand side of Fig. 6(d), is not modeled in the simulations as the cell size in the growth direction of the film is set to 50 nm.

FIG. 6. (a),(b) Simulated profiles of spin waves that are excited by a 40-GHz global excitation field. In the simulations, $\mu_0 H_{\text{ext}} = 60$ mT and $\theta = 45^\circ$. The magnetization in the two stripe domains is nonresonantly driven by the excitation field. Because the domains exhibit different effective magnetic fields, the amplitude of the oscillations are different such that at the boundary, a time-dependent $\text{div } \mathbf{M} \neq 0$ is produced that launches the spin waves. The snapshots in (a) and (b) are recorded with a phase difference of about 75° in the microwave excitation signal. (c) Two-dimensional profile of emitted spin waves at 40 GHz. (d) Simulated (symbols) and calculated (lines) dispersion curves for spin waves propagating into domains with large effective field (H_{ext} parallel to the UMA) and domains with small effective field (H_{ext} perpendicular to the UMA).

V. DISCUSSION AND CONCLUSIONS

We show that confined and propagating spin waves are excited by spatially uniform magnetic field excitation in strain-coupled $\text{BaTiO}_3/\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ heterostructures. In this multiferroic bilayer system, stripe domains of the ferroelectric substrate are imprinted into the continuous ferromagnetic film via inverse magnetostriction. As the ferroelectric domain boundaries are straight and only a few nanometers wide, the strain-induced magnetic anisotropy in the $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ film alters at precise locations. In combination with an external bias field, this anisotropy pattern produces regular modulations of the effective magnetic field. Stripe domains with small and large effective field alternate, and transitions between the two levels are abrupt. This unique configuration, which is a direct consequence of strain coupling to regular ferroelectric stripe domains in BaTiO_3 , cannot be attained by dipolar magnetic fields in lithographically defined structures. If the system is excited by a global microwave field, three main effects occur: First, domains with small effective magnetic field act as potential wells. As a consequence, standing spin waves are excited at frequencies where the dispersion curve of the domain matches $k = n\pi/w$. Second, magnetic excitations in domains with large effective magnetic field cause emission

of short-wavelength spin waves into neighboring regions. Third, dynamic fluctuations of the effective magnetic field at single-anisotropy boundaries lead to the excitation of exchange-dominated spin waves. In both emission processes, the wavelength of propagating spin waves is highly tunable by rotation of an external bias field. The ability to tune the emission of short-wavelength spin waves at well-defined locations within a continuous ferromagnetic film is a promising feature for nanoscale magnonics.

Beyond these results, multiferroic heterostructures possess additional features that can be exploited in magnonic devices. Electric-field-driven motion of magnetic domain walls, as demonstrated recently [34], can be used to actively control the width of stripe domains. In the hybrid system considered here, such a change in domain width implies that the resonance frequency of confined spin-wave modes shifts, and the wavelength and frequency of propagating modes alter by pure electrical means. The latter effect is illustrated by considering the dots on the red dispersion curve of Fig. 5(c). If the width of the domain with larger internal magnetic field is changed by an electric field, the resonance conditions move along the dispersion curve. Via mode conversion, this shift in the resonance condition changes the wavelength and frequency of emitted spin waves. The long and straight anisotropy boundaries that are induced by strain transfer in $\text{BaTiO}_3/\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ can also be exploited to coherently excite short-wavelength spin waves in multiple waveguides. For example, if magnetic wires are patterned perpendicular to the stripe domains, the anisotropy boundaries are perfectly aligned. In this case, one microwave antenna can simultaneously excite spin waves in different wires with the same amplitude and phase, which can be used in spin-wave interference devices [35,36]. Finally, we note that the emission of short-wavelength spin waves from partially confined spin-wave modes or abrupt anisotropy boundaries can also be attained in other anisotropy-modulated material systems. The required variation of magnetic anisotropy can, e.g., be induced by focused-ion-beam irradiation of a ferromagnetic antiferromagnetic bilayer [37] or oxygen ion migration from an adjacent metal-oxide layer [38].

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