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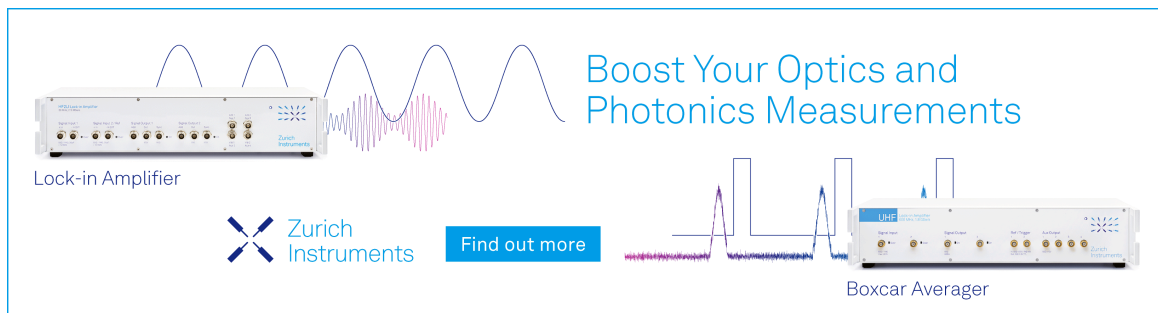
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ABSTRACT

Spin waves, known for their ability to propagate without the involvement of moving charges, hold immense promise for on-chip information transfer and processing, offering a path toward post-CMOS computing technologies. This study investigates the potential synergy between propagating Damon–Eshbach spin waves and voltage-controlled magnetization in the pursuit of environmentally sustainable computing solutions. Employing micromagnetic simulations, we assess the feasibility of utilizing spin waves in DE mode in conjunction with localized voltage-induced alterations in surface anisotropy to enable low-energy logic operations. Our findings underscore the critical importance of selecting an optimal excitation frequency and gate width, which significantly influence the efficiency of the phase shift induced in propagating spin waves. Notably, we demonstrate that a realistic phase shift of $2.5 [\pi \text{ mrad}]$ can be achieved at a Co(5 nm)/MgO material system via the voltage-controlled magnetic anisotropy effect. Moreover, by tuning the excitation frequency, Co layer thickness, gate width, and carefully selecting the dielectric layer, we extrapolate the potential to enhance the phase shift by a factor of 200 when compared to MgO dielectrics. This research contributes valuable insights toward developing next-generation computing technologies with reduced energy consumption.

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The use of magnonics in the context of wave-based computing has gained interest for its potential use as a low Ohmic-loss information carrier. Unlike conventional electronics, where information is conveyed through electronic charges, magnonics employ spin waves (SWs) to carry information through the amplitude and phase of a pseudo-particle known as a magnon. This innovative approach may open the road to beyond-CMOS computing technology^{1–3} free of Joule heating. As data processing requires phase and amplitude modulation, novel ways of manipulating propagating SWs through a local change in the effective magnetic field have been explored, such as the application of a magnetic field,^{4–6} local laser-induced heating,^{7–9} or current.^{10–12} In particular, control of phase or amplitude by Oersted field or SW current has been a topic of study for the development of Mach–Zehnder spin-wave interferometer architecture.^{13–15} In an effort to further decrease the energy consumption of magnetic

materials-based computing devices, voltage-controlled magnetic anisotropy (VCMA) holds great promise, potentially reducing the energy consumption of storage and logic devices by a factor of 100.¹⁶ Effects of an electric field on surface anisotropy (SA) have widely been studied over the recent years^{17–25} and, in essence, can be used to manipulate the spin-wave (magnon) dispersion relation via two routes: a fast, volatile, electronic effect, e.g., direct solid-state gating, or a slow, nonvolatile, magneto-ionic effect, e.g., moving mobile ions in or out of the ferromagnetic layers. The magneto-ionic effect is a process of electrochemical nature happening at ferromagnetic/oxide (FM/O) interfaces,²⁶ where oxygen ions are brought to the interface between the oxide dielectric and the ferromagnetic layer. Due to coupling between 2p orbitals of oxygen ions and 3d orbitals from Co at the interface,²⁷ changes in charge densities lead to a change in the magnetic anisotropy via a modulated spin-orbit coupling. The magneto-electronic effect

has been interpreted as a change in the electronic occupation state at the interface between the dielectric and the ferromagnetic layer^{28–30} and electric field-induced dipole.³¹ While volatile, the latter effect is particularly suited for logic due to the fast transport of the charges at the interface, compared to magneto-ionic effects befitting for storage devices due to their non-volatility but slower response due to the electrochemical nature.

Theoretical and experimental studies based on VCMA control of SWs include reconfigurable magnonic crystals,³² nanochannels,^{32,33} and SW phase shifters.^{34,35} Moreover, these studies have primarily been focusing on insulating ferromagnetic SW conduits of yttrium iron garnet (YIG).^{36,37} In particular, studies have concentrated on the Damon–Eshbach (DE) SW mode configuration. Indeed, due to the localization of DE SWs at the interfaces of the ferromagnetic layer in direct contact with the dielectric where the VCMA effect is induced, the VCMA-induced non-reciprocal transport of the SWs can efficiently be probed using a phase-sensitive all-electrical method.^{38–40} In these studies, the VCMA effect was assumed to be applied homogeneously along the entire spin-wave conduit. Hence, the question of what happens when the VCMA effect is applied locally along the path of a spin-wave conduit remains open.

In this study, we present an investigation of the impact of locally applied electric fields at the interface between a Co ferromagnetic layer and an MgO dielectric on dipole-dominated DE propagating SWs within thin-film SW conduits, employing Mumax³ micromagnetic simulations.⁴¹ Initially, we elucidate the influence of SA modifications on the dispersion characteristics of the excited modes, shedding light on their implications for the wavevector of SWs both entering and exiting the VCMA-gated region. Subsequently, we examine the propagation characteristics of the resulting scattered SWs. Furthermore, we analyze the frequency and gate width-dependent VCMA-induced phase shifts in the scattered SWs at a local scale. Finally, we discuss the feasibility of employing the DE configuration for SW phase shifting with a metallic Cobalt ferromagnetic waveguide and optimizing the ferromagnetic/dielectric interface.

Our model system is a 8192 nm long (x) and 64 nm (y) wide Co waveguide with a thickness of 5, 10, and 20 nm (z). The simulation box is subdivided in $2 \times 2 \times 2.5$ nm³ cells in the x -, y -, and z -directions. Due to the narrowness of our waveguide and our focus on the lowest frequency DE mode, i.e., the wavevector along (y) $k_y = 0$,

periodic boundary conditions (PBCs) are applied along y . The used magnetic parameters for Cobalt are $\gamma = 1.9 \times 10^{11}$ Hz rad/T, $M_s = 1.42 \times 10^6$ A/m, $A_{ex} = 20 \times 10^{-12}$ J/m, and $\alpha = 0.005$, respectively, representing the gyro-magnetic ratio, the saturation magnetization, the exchange stiffness, and the damping, respectively. No uniaxial anisotropy is introduced. Exponentially increasing spatial damping profiles over a distance of 1.016 μ m are introduced at both ends (x) of the simulation box to prevent SW reflections. DE SWs are excited by applying a static transverse magnetic field of 100 mT along y , fully saturating the magnetization in the y -direction. A sinusoidal AC magnetic field with a Gaussian profile varying in the x -direction is applied for a time period of $t = 10$ ns to model the effect of an antenna of width $W_a = 40$ nm, leading to the excitation of a spin wave with small time-dependent dynamic magnetization components in the x - z plane.

In the following, we define three regions [see Fig. 1(a)]. In regions 1 and 3, the base anisotropy $K_{S_{E=0}} = 0.71 \times 10^{-3}$ J/m² is chosen following Kasukawa *et al.*,³⁸ with the subscript $S_{E=0}$ indicating the nominal anisotropy of the waveguide, i.e., when no VCMA is applied. In region 2, we emulate the effect of VCMA, e.g., by solid-state gating, by modifying the magnetic anisotropy to $K_{S_{E \neq 0}}$. In region 1, an AC field located 1.2 μ m away from the left edge of the waveguide is responsible for exciting SWs propagating to the left ($-x$) and right ($+x$) directions. The SWs traveling to the right first encounter region 2 and finally propagate to region 3, where we detect the SWs after scattering twice at the entry and exit of region 2 due to the modified SA $K_{S_{E \neq 0}}$ in that region. The SW propagating to the left of the waveguide is absorbed due to the exponentially increasing α , which prevents SW reflection at the left edge.

In this article, data are extracted by defining a row of cells of $2 \times 2 \times 2.5$ nm³ at the top surface of the strip along the x -direction of the strip, centered around $y = 32$ nm [see Fig. 1(b)]. As the spin-wave profile is uniform across the thickness, we choose this region to minimize simulation time, saving only data from the selected region. The region is selected around the center of the strip to avoid peculiarities in the demagnetizing field due to edge effects. A fast Fourier transform (FFT) in space and time of the dynamic magnetization m_x component in this box allows us to obtain the dispersion relation of our system as shown in Fig. 2(a). The highest intensity of the FFT follows very closely the analytical dispersion (shown by the red dashed line) given as⁴²

$$f = \frac{\mu_0 \gamma}{2\pi} \sqrt{\left(H + \frac{2A_{ex}}{\mu_0 M_S} k^2\right) \left(H + \frac{2A_{ex}}{\mu_0 M_S} k^2 + M_S - H_p(V_{gate})\right) + \frac{M_S}{4} (1 - e^{-2t|k|})(M_S - H_p(V_{gate}))}, \quad (1)$$

where H is the applied static magnetic field, k is the SW wavevector, and $H_p(V_{gate})$ is the voltage (V_{gate})-dependent out-of-plane SA field. From this excellent correspondence, we conclude that our micromagnetic simulation setup correctly describes DE-mode SWs in Co-based thin films. Once the SWs are excited in region 1, they propagate to region 2, at the center of the strip, where the effective $K_{S_{E \neq 0}}$ is modified to reproduce the VCMA effect induced at the interface between the Co and the MgO. Here, we include the VCMA effect as a linear dependency on the applied electric field.⁴³ The

voltage-dependent out-of-plane SA $H_p(V_{gate})$ can be expressed as $\beta \frac{2K_S}{\mu_0 M_S t_{CO}}$, where t_{CO} is the thickness of the Co layer and β is a linear term with V_{gate} describing the effect of the electric field on the change of K_S . Here, we have used the value based on the work of Kasukawa *et al.* multiplied by ten to boost the effect in our simulations, which corresponds to a relative change in the total perpendicular magnetic anisotropy of 0.44%. Once the SWs leave region 2, they are detected in region 3, where the anisotropy is set to $K_{S_{E=0}}$ as in region 1. In our following simulations, we vary the gate width

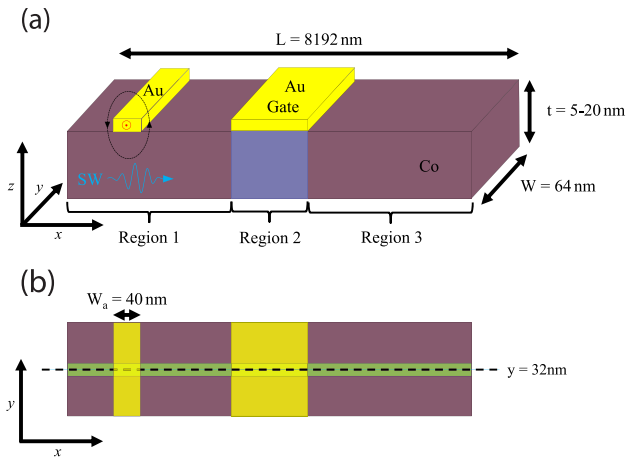


FIG. 1. (a) Schematic of the system under study. The strip is divided into three regions. The SW is excited in region 1, K_S is modified within region 2, under the gate, and the SW is detected in region 3. (b) Top view of the simulation box. A row of cells (in green) of $2 \times 2 \times 2.5 \text{ nm}^3$ centered around the center of the strip ($y = 32 \text{ nm}$) along which the magnetization is sampled.

(W_{gate}) from 0 to $2.5 \mu\text{m}$, and K_S is increased (respectively, decreased) by a maximum amount of $3 \times 10^{-3} \text{ mJ/m}^2$.

The effect of the change in K_S can be understood from the inset of Fig. 2(a), which shows a change in the dispersion, under the gated region, for different K_S . Once K_S is increased by $+\Delta K_S$ (respectively decreased by $-\Delta K_S$), the dispersion relation is shifted down (respectively up). Let us now assume an SW excited with a wavevector $k = 5 [2\pi \text{ rad}/\mu\text{m}]$. An increase in anisotropy $+\Delta K_S$ (respectively, decrease in anisotropy $-\Delta K_S$) will result in a scattering of the SW to a wavevector k_2 (respectively k_1). By numerically solving Eq. (1) for the wavevector k , we plot, in Fig. 2(b), the change in wavevector $\Delta k = |k_0\% - k_{-0.44\%}|$ with $k_0\%$ the initial SA and $k_{-0.44\%}$ the SA corresponding to a decrease in 0.44% of $k_0\%$. As K_S is an interfacial effect, the VCMA effect scales as $1/t_{Co}$. The dependency of Δk with increasing frequency can be understood via its dispersion relation. For all thicknesses, Δk increases with frequency, which is a direct consequence of the flattening of the dispersion relation at higher frequencies [e.g., Fig. 2(a)], which increases the change in Δk for a given change in K_S . The consequence of a change in wavevector is a phase shift of the propagating SW induced in the gated region. Therefore, an increase (decrease) in SA results in a decrease (increase) of wavevector, inducing a positive phase shift due to its higher (lower) group velocity (v_g). Hence, we conclude that, in accordance with the analytical dispersion, the total amount of acquired phase shift per unit length (due to the Δk) of a SW traveling through the gated region 2 strongly depends on the conduit layer thickness via its dispersion.

Figure 3(a) shows the normalized M_x/M_S component of the magnetization along the x -axis of the waveguide. To compare our results, we choose the same time instant of the M_x/M_S component, corresponding to the last time frame of the simulation ($t = 10 \text{ ns}$). This ensures that the amplitude of M_x/M_S over time does not vary and corresponds to the magnetization equilibrium. As described previously, an exponential damping profile is present at both ends of the waveguide in the gray areas [see Fig. 3(a)]. As seen in Fig. 3(a), the SW is excited $1.2 \mu\text{m}$ from the left side of the strip, noted by a red dashed

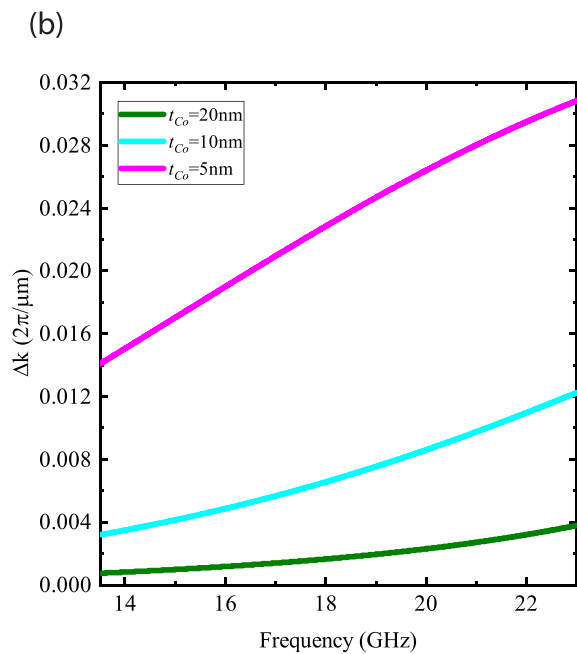
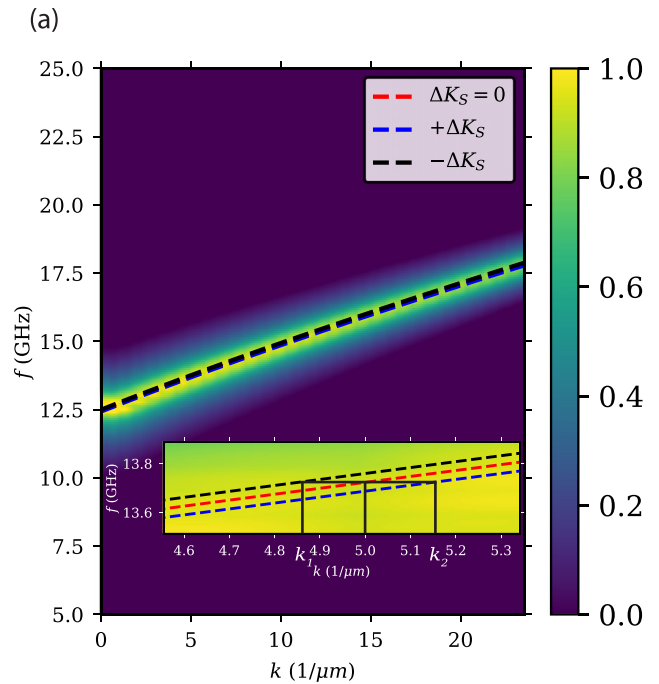


FIG. 2. (a) FFT of M_x/M_S component of micromagnetic simulation for a Co ($t_{Co} = 5 \text{ nm}$) waveguide. The inset shows the effect of a change in K_S on the dispersion from Eq. (1). (b) Numerically deduced change in wavevector due to the VCMA as a function of frequency for $t_{Co} = 5, 10,$ and 20 nm waveguides using Eq. (1).

line, corresponding to the position of the center of the antenna. The two continuous black lines centered around the center of the strip, and delimiting the purple region, indicate the gated region with a width of $W_{gate} = 1.1 \mu\text{m}$. The amplitude of M_x/M_S shows the typical

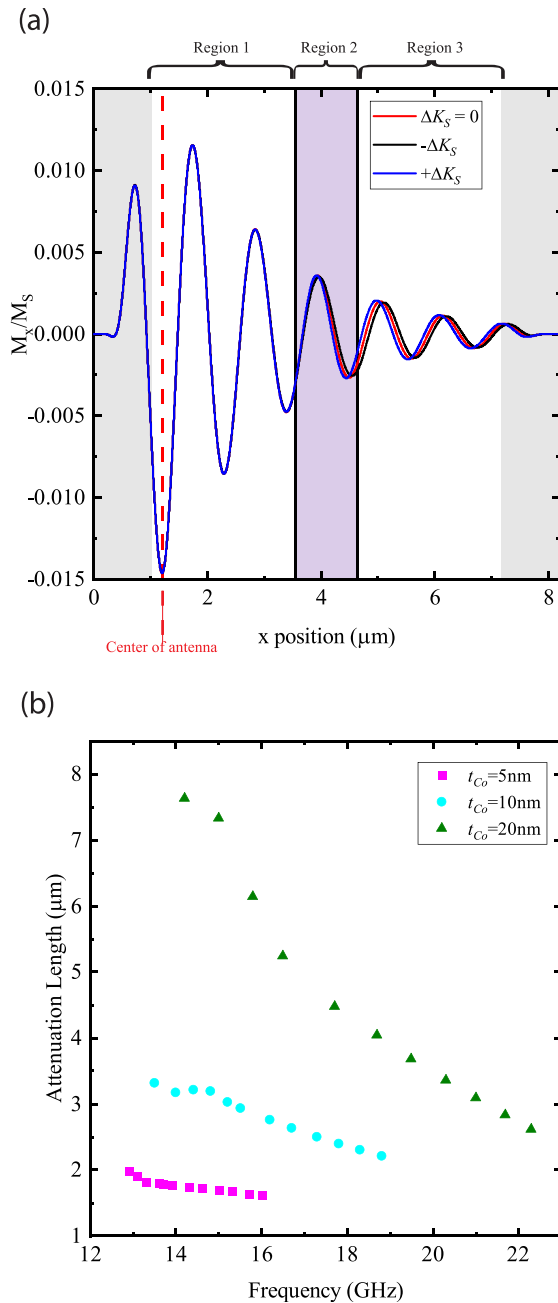


FIG. 3. (a) M_x/M_S component of the magnetization along x at time instant $t = 10$ ns for a $t_{Co} = 5$ nm layer for no change in anisotropy in red, a positive change in blue, and a negative change in black. Numbers 1, 2, and 3 correspond, respectively, to regions 1, 2, and 3 shown in Fig. 1 with region 2 delimited by the 2 continuous black lines. (b) Fitted attenuation length l_{att} ($t = 10$ ns) as a function of frequency excitation of SWs for $t_{Co} = 5, 10,$ and 20 nm.

exponential decay with distance due to damping. Once K_S is decreased (respectively increased) by a factor $-\Delta K_S$ (respectively $+\Delta K_S$) in the gated region as shown by the blue curves, a positive (respectively negative) phase shift is induced in the gated region, which, after traveling

into region 2, results in a constant phase shift-propagating SW that can be measured in region 3. Due to the small change in k , no significant backscatter effects are observed at the interfaces between regions 1 and 2 and regions 2 and 3. This simple representation captures, in essence, the effect of VCMA on the phase change of the SWs. However, using these profiles, we can extract the effect of gating on the SW attenuation length l_{att} as a function of the frequency for different t_{Co} , as shown in Fig. 3(b). To do so, we fit the M_x/M_S component of the magnetization along the x with the following expression:

$$A e^{-l_{att}x} \sin(kx + \phi), \quad (2)$$

where A is the amplitude, l_{att} is the attenuation length, x is the position along the x -axis of the waveguide, k is the wavevector, and ϕ is the phase of the SW. As expected, l_{att} decreases with increasing frequency as the dispersion relation flattens off, resulting in a lower v_g . Moreover, the thinner the Co layer, the lower the v_g in the studied frequency regime, resulting in a smaller attenuation length. Hence, as the SW phase accumulates with the distance traveled, one must carefully balance the attenuation length and accumulated phase shift per unit length.

In order to extract the accumulated phase of the propagating SW in region 3, resulting from the local VCMA-induced change in wavevector in region 2, we use Eq. (2) to fit the portion of the SW in region 3 of interest. Here, we define the phase shift as $\Delta\phi_{+-} = |\phi_{0\%} - \phi_{\pm 0.44\%}|$, i.e., the difference between the phase of the SW with wavevectors $k_{0\%}$ and $k_{\pm 0.44\%}$ and $k_{0\%}$ and $k_{-0.44\%}$. To compensate for the thickness-dependent change in the accumulated phase due to the change in v_g , in Fig. 4, we plot Δk multiplied by the wavevector-dependent v_g as extracted from the dispersion relation. As expected from the model from Eq. (1), the VCMA-induced phase shift scales linearly with the change in K_S . Moreover, we identify the necessity to multiply the phase by the v_g in

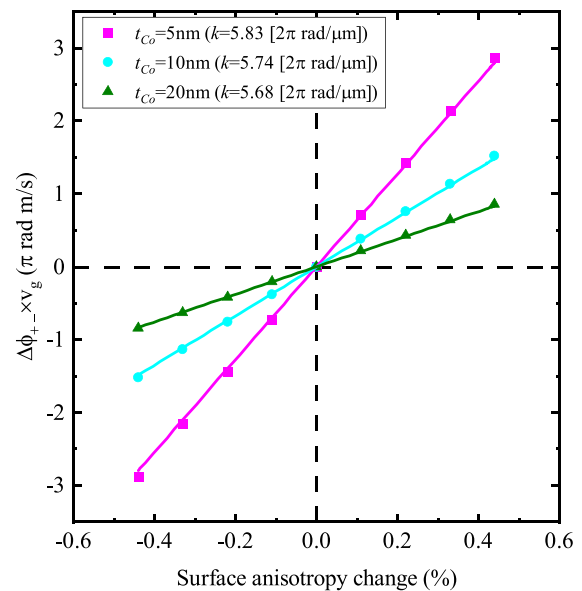


FIG. 4. Phase shift ($t = 10$ ns) multiplied by the frequency-dependent v_g as a function of K_S change for $t_{Co} = 5, 10,$ and 20 nm from micromagnetic simulations (symbols) and analytical model (continuous lines).

order for the accumulated phase to scale as $1/t_{Co}$. This suggests an effect of VCMA on the phase inversely proportional to v_g , implying a time-dependent effect of VCMA on the propagating SW, in the gated region. Changes in the amplitude and phase of the propagating SW due to local VCMA can be compared. For a 5 nm Co magnetic layer, changes in amplitude were found to be several times smaller than phase changes for an equivalent surface anisotropy change. This suggests that an efficient VCMA modulation of amplitude in the DE dipole-dominated mode remains significantly smaller than phase modulation. As a result, the effect of VCMA on the amplitude of propagating SW is considered too small to be relevant to this study.

Performing full logic operations with SWs requires a π rad shift of the SW compared to a given SW reference signal. Although t_{Co} can be reduced to boost the VCMA effect and, therefore, the phase shift, a reduction in thickness is limited in its efficiency due to the decreased l_{att} . Figure 5(a) shows the phase shift $\Delta\phi = |\phi_0\% - \phi_{-0.44\%}|$ as a function of the gate length for wavevectors of 5.84, 8.35, and 10.51 [2π rad/ μm] for a Co layer of $t_{Co} = 5$ nm. As expected from the analytical model from Eq. (1), we observe a linear increase in the $\Delta\phi$ with increasing W_{gate} . Good correspondence between the analytical model ($\Delta k \times W_{gate}$) and the simulations shows that the analytical model can accurately predict phase changes induced by VCMA.

To gain further insight into the frequency dependency of the VCMA effect, we plot the $\Delta\phi$ as a function of the SW frequency in Fig. 5(b). Indeed, as v_g decreases with SW frequency and Co layer thickness, the accumulated phase increases for a given W_{gate} . A discrepancy between the micromagnetic and analytical model is observed for lower wavevector (open symbols) and is currently speculatively attributed to reflections and/or finite size effect of the simulation box which becomes of the order of the SW wavelength. The linear trend in the VCMA-dependent $\Delta\phi$ with the excitation frequency and W_{gate} allows for a discussion on the feasibility of a π rad phase shift induced by a local change in K_S for the application of logic operation. Let us assume, as an example, a wavevector $k = 8.35$ [2π rad/ μm] and W_{gate} of 1.5 μm . Assuming minimum reflections from the gated area and no resonance in the gated region due to the SW wavelength being commensurable with the gated region width, we can naively deduce, from Fig. 5(a), that the maximum possible achievable $\Delta\phi$, in these conditions, is of the order of 12.6 [π mrad] when using an MgO dielectric as a catalyst for the change in K_S . In this work, we have multiplied the assumed changes of SA in Kasukawa *et al.*, by ten in order to enhance the effect in the simulation. As a result, a realistic VCMA-induced K_S change can be expected to produce a $\Delta\phi$ of 1.26 π mrad, without any boosting. It is important to note that as a positive change in K_S will induce an additional $\Delta\phi$ of 1.26 [π mrad] due to the symmetrical $\Delta\phi$ induced by a change in SA, the total $\Delta\phi$, in these conditions, would be 2.5 [π mrad]. While we think this phase change is commensurable with the limit of phase sensitivity of the all-electrical propagating SW spectroscopy measurement methods,⁴⁴ an optimization of the excitation frequency and W_{gate} is needed to achieve phase changes in the order of the π rad phase shift. Although MgO does not allow for significant changes in K_S , optimizing the dielectric layer may considerably increase the efficiency of VCMA-induced $\Delta\phi$ with DE SWs. One possibility is the use of a GdO_x dielectric, which showed an efficiency of change in K_S in the order of 500 fJ/(V m) at Co ($t_{Co} = 0.9$ nm)/ GdO_x ($t_{\text{GdO}} = 3$ nm) interfaces.²⁵ This efficiency in VCMA is 200 times superior to MgO, which could potentially increase the $\Delta\phi$ to a value of

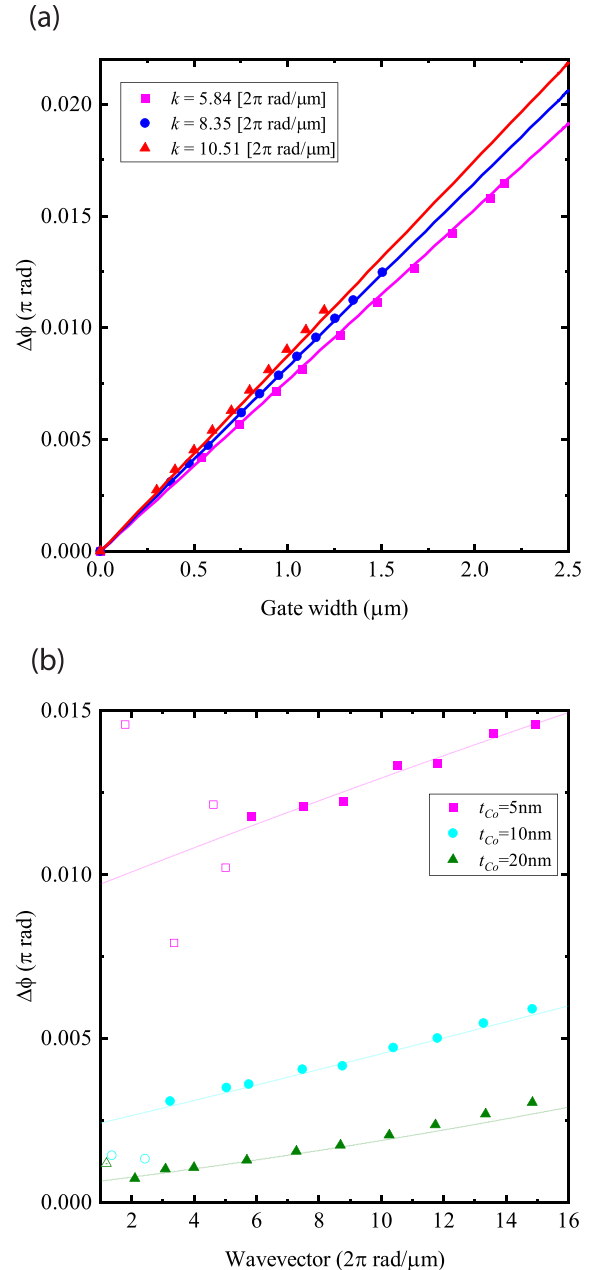


FIG. 5. (a) Phase shift ($t = 10$ ns) as a function of the W_{gate} for a $t_{Co} = 5$ nm waveguide and wavevectors 5.84, 8.35, and 10.51 [2π rad/ μm] as obtained from micromagnetic simulations (symbols) and analytical model (solid lines). (b) Phase shift ($t = 10$ ns) as a function of the SW wavevector for a $t_{Co} = 5$ nm waveguide from micromagnetic simulations (symbols) and analytical model (solid lines). A discrepancy between the micromagnetics and the analytical model is observed for a lower wavevector as denoted by the open symbols.

0.25 [π rad]. By tuning the applied voltage within the breakdown limit of GdO_x and optimizing the excitation frequency and W_{gate} , we could, therefore, imagine further improvement in the efficiency of the $\Delta\phi$. However, the use of GdO_x presents a significant limitation in time

efficiency due to the oxidation mechanism responsible for the change in K_S . On top of tuning the parameters previously described, the efficiency of VCMA of $\Delta\phi$ is also shown to scale as $1/t_{Co}$, meaning that a thinner layer would improve further the efficiency of VCMA and get closer to a π rad phase shift. It is important to note that the effect of VCMA on interfacial Dzyaloshinskii–Moriya interaction (iDMI) has not been included in this study, but further research in the combination of the VCMA effect on K_S and iDMI may lead to even more significant changes in phase as VCMA effects have been reported on iDMI.³⁹

In summary, we have investigated the effect of a local change in K_S on the phase of the propagating SWs in the DE configuration. We have shown a linear dependency of the VCMA-induced $\Delta\phi$ with the excitation frequency and W_{gate} in accordance with analytical models. Moreover, we showed the importance of the v_g in the expected $\Delta\phi$ when studying the effect of a change in t_{Co} . We determined that the maximum realistic $\Delta\phi$ in Co ($t_{Co} = 5$ nm)/MgO stack is of the order of $2.5 [\pi \text{ mrad}]$ and can be further improved by increasing the frequency excitation, W_{gate} , decreasing t_{Co} and by optimizing the choice of the dielectric layer, the latter allowing to improve the efficiency of change in phase by a factor of 200 compared to what can be expected from an MgO dielectric.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Adrien A. D. Petrillo: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Writing – original draft (lead); Writing – review & editing (lead). **Mouad Fattouhi:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Adriano Di Pietro:** Conceptualization (supporting); Formal analysis (supporting); Writing – original draft (equal); Writing – review & editing (supporting). **Marta Alerany Solé:** Conceptualization (supporting); Formal analysis (supporting); Writing – review & editing (supporting). **Luis Lopez Diaz:** Conceptualization (supporting); Methodology (supporting); Supervision (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Gianfranco Durin:** Writing – review & editing (supporting). **Bert Koopmans:** Conceptualization (supporting); Supervision (supporting); Writing – review & editing (supporting). **Reinoud Lavrijsen:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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