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Spin-Cherenkov effect in a magnetic nanostrip with interfacial Dzyaloshinskii-Moriya interaction

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Spin-Cherenkov effect enables strong excitations of spin waves (SWs) with nonlinear wave dispersions. The Dzyaloshinskii-Moriya interaction (DMI) results in anisotropy and nonreciprocity of SWs propagation. In this work, we study the effect of the interfacial DMI on SW Cherenkov excitations in permalloy thin-film strips within the framework of micromagnetism. By performing micromagnetic simulations, it is shown that coherent SWs are excited when the velocity of a moving magnetic source exceeds the propagation velocity of the SWs. Moreover, the threshold velocity of the moving magnetic source with finite DMI can be reduced compared to the case of zero DMI. It thereby provides a promising route towards efficient spin wave generation and propagation, with potential applications in spintronic and magnonic devices.

The Cherenkov radiation of light¹ occurs when a charged particle moves faster than the light speed within a medium. This effect is named after Pavel Alekseyevich Cherenkov, who studied this phenomenon experimentally. Cherenkov radiation is used frequently in particle identification detectors in particle physics². The Cherenkov effect is analogous to the sonic boom produced by shock waves propagating away from an aircraft, if its speed exceeds the sound velocity. Similar to the Doppler effect observed in different physical system^{3–7}, the Cherenkov effect belongs to one of the fundamental phenomena induced by the radiation of moving sources. The Cherenkov-like effect of SWs has been theoretically studied in ferromagnets, which can be used to excite coherent SWs without the necessity of external alternating magnetic field or current^{8,9}. Recently, the study of the influence of the antisymmetric exchange interaction, namely the Dzyaloshinskii-Moriya interaction (DMI), on magnetic excitations such as domain walls and vortex is one of the hottest topics in nanomagnetism and spintronics^{10–20}. DMI is an antisymmetric interaction induced by spin-orbital coupling due to broken inversion symmetry in lattices or at the interface of magnetic films¹², which has been measured for both magnetic interfaces^{21,22} and bulk materials^{23,24}. DMI facilitates the creation of topologically protected spin textures in chiral magnetic materials, i.e. magnetic skyrmions, which are favorable information carriers in the next-generation data storage and spin logic devices. On the other hand, theoretical^{13,14,16} and experimental^{10,15,25} studies have demonstrated that DMI leads to an asymmetrical spin-wave dispersion. DMI has also been measured in a wide range of materials including permalloy^{22,26,27}. Specifically, the asymmetry in the formation of a vortex state in a permalloy nanodisk has been studied by micromagnetic simulations with interfacial DMI²².

In this paper, the influence of interfacial DMI on the Spin-Cherenkov effect (SCE) in permalloy strip are studied by micromagnetic simulations. Pictorial illustrations of the setup is shown in Fig. 1, where a rectangular moving magnetic field pulse is applied to the permalloy strip with a magnitude of 10 mT along the $+z$ -direction. Our numerical results show that the interfacial DMI leads to a reduction of the threshold velocity of moving source, i.e. the minimum SW phase velocity, for coherent SW excitation in the absence of external ac magnetic field. Therefore it provides a promising route to reducing SCE threshold to facilitate experimental realization of such effect in magnetic medium.

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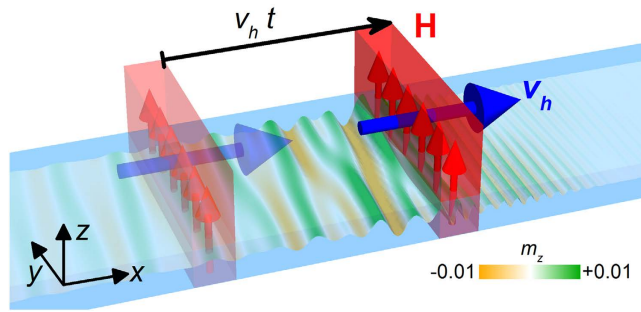


Figure 1. Schematics of the micromagnetically modeled system. An external rectangular shape field pulse (H), 12 nm wide in the x -direction and 100 nm long in the y -direction, is applied to a 12- μm -long, 100-nm-wide, and 10-nm-thick magnetic strip with a magnitude of 10 mT in the z -direction and constant speed of v_h . The color scale represents the out-of-plane component of the magnetization m_z , which has been used throughout this paper.

Results

SW excitation via SCE in permalloy strips. The response of the magnetization distribution to the pulse velocity v_h is shown in Fig. 2. A localized magnetic field of constant magnitude traveling along the wire axial direction with velocity of v_h , is applied to mimic the interacting force with the magnetization. The magnetization dynamics is strongly dependent on the pulse velocity v_h . For $D = 0 \text{ mJ m}^{-2}$ and $v_h = 500 \text{ m s}^{-1}$ and 900 m s^{-1} (see Fig. 2(a1,a2)), the moving magnetic field pulse only causes a distortion of the magnetization distribution traveling with the pulse. There is no spin wave (SW) excitation by the moving pulse. As the velocity of the magnetic pulse increases, SW excitations are observed for $v_h = 1050 \text{ m s}^{-1}$, 1100 m s^{-1} and 1200 m s^{-1} , as shown in Fig. 2(a3–a5). At $v_h = 1050 \text{ m s}^{-1}$, the SWs preceding the source and lagging the source are well-distinguished with different wave lengths. Upon the application of a moving dc magnetic field pulse, the system reaches a dynamic equilibrium and the excited spin waves comprise of two branches, giving rise to the SCE as reported in Ref. 9.

For the permalloy nanostrip with interfacial DMI, similar magnetization dynamics occur as the moving field pulse is applied. For the case of $D = 1 \text{ mJ m}^{-2}$, there is no SW excitation by the moving magnetic field with the speed of $v_h = 500 \text{ m s}^{-1}$ and 900 m s^{-1} . The Cherenkov emission of SWs emerge at $v_h = 1050 \text{ m s}^{-1}$, 1100 m s^{-1} and 1200 m s^{-1} in the permalloy strip as shown in Fig. 2(b3–b5). The SWs excited in permalloy nanostrip are distorted due to the presence of DMI. The interfacial DMI term for any in-plane direction \mathbf{u} can be expressed as $D\mathbf{z} \times \mathbf{u}$ ²⁸, which may be treated as an effective field transverse to the magnetic track, resulting in the distorted spin waves. As $D = 2 \text{ mJ m}^{-2}$, spin wave is excited when $v_h = 900 \text{ m s}^{-1}$, indicating that the presence of interfacial DMI leads to the decreasing of the threshold velocity of the moving field source for spin wave excitation. It should be noticed that the SWs with more significant distortions are observed at $v_h = 1050 \text{ m s}^{-1}$, 1100 m s^{-1} and 1200 m s^{-1} as shown in Fig. 2(c3–c5). Moreover, the difference between the SW branches preceding and lagging the source becomes even more obvious with increasing DMI strength for a given pulse velocity.

Figure 3 shows the numerically determined SW phase velocity $v_p(k)$ and group velocity $v_g(k)$ for $D = 0 \text{ mJ m}^{-2}$. The inset of Fig. 3 shows the SW dispersion in the permalloy strip, which agrees well with the analytical results for zero DMI (proportional to k^2). In Fig. 3, the phase velocity v_p and v_g of the SWs are extracted from the dispersion relation of $v_p(k) = \omega/k$ and $v_g(k) = d\omega/dk$. The minimum of the phase velocity occurs around 1000 m s^{-1} , meaning that no SW is excited by the moving field pulse in the permalloy strip for the pulse velocities below the minimum v_0 . In other words, the velocity v_0 is the threshold velocity of SCE, below which there is no coherent SWs excitation. As the field pulse moves at a velocity larger than v_0 , there are two SW modes excited with different group velocity v_g but equal phase velocity v_p . The SW packet with larger k ($v_g > v_p$) moves in the front of the source and leaves the one with smaller k ($v_g < v_p$) behind. The field pulses with different velocity v_h are applied and the corresponding responses of the magnetization distribution are shown in Fig. 2(a1–a5). The calculated k are shown with color stars in Fig. 3. As v_h is below the critical velocity, there is no SW excitation by the moving field pulse. When $v_h = 1050 \text{ m s}^{-1}$, there are two SW modes observed in the permalloy strip. The spin waves formed in front of and behind the pulse exhibit different characteristics in Fig. 2(a3), and the corresponding k values are shown in Fig. 3. The Cherenkov emission of SWs can also be observed for the case of $v_h = 1100 \text{ m s}^{-1}$ and 1200 m s^{-1} . The dispersions are in an excellent agreement with the curves of $v_p(k)$ and $v_g(k)$. The curves of $v_p(k)$ and $v_g(k)$ extracted from the numerical SW dispersion relation $\omega(k)$, which is obtained by applying a localized ac field and extracting the wavelength of the excited spin waves, can predict the Cherenkov excitation of SWs precisely.

Influence of DMI on SCE in permalloy. Figure 4 shows the numerically determined phase velocity $v_p(k)$ and group velocity $v_g(k)$ with $D = 2 \text{ mJ m}^{-2}$, where $v_p(k)$ and $v_g(k)$ are calculated from the SW dispersion relation $\omega(k)$ shown in the inset. Similar to the case of $D = 0 \text{ mJ m}^{-2}$, there exists a critical velocity v_0 for the Cherenkov excitation of SWs. The Cherenkov excitation of SWs can be observed for $v_h > v_0$ (887 m s^{-1}). We also investigate the evolution of the SW branches by varying v_h for $D = 2 \text{ mJ m}^{-2}$. At $v_h = 1050 \text{ m s}^{-1}$, the Cherenkov excitation of SWs is observed with two SW modes formed in the permalloy strip. The calculated k marked with color stars agrees very well with the numerically determined curve of $v_p(k)$. The curves of $v_p(k)$ and $v_g(k)$ extracted from the

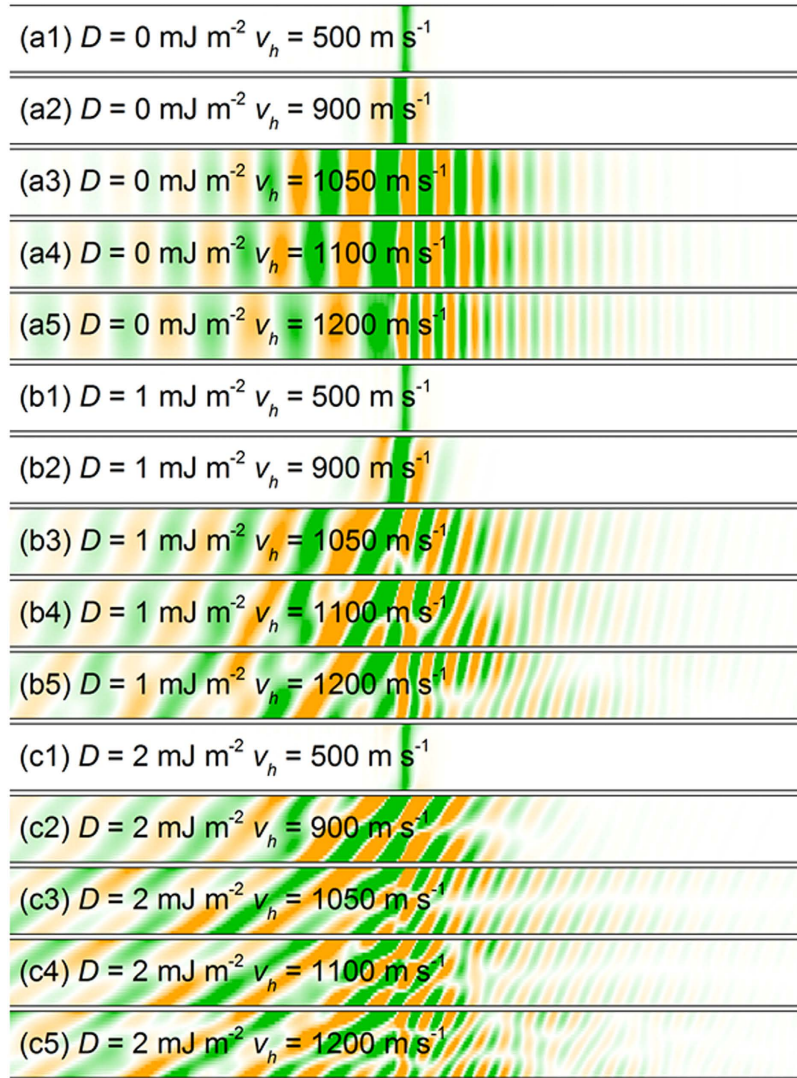


Figure 2. Snapshots of the z -component of the magnetization in a magnetic strip in the vicinity of the field pulse traveling at a constant speed. (a1) $D = 0 \text{ mJ m}^{-2}$ and $v_h = 500 \text{ m s}^{-1}$, (a2) $D = 0 \text{ mJ m}^{-2}$ and $v_h = 900 \text{ m s}^{-1}$, (a3) $D = 0 \text{ mJ m}^{-2}$ and $v_h = 1050 \text{ m s}^{-1}$, (a4) $D = 0 \text{ mJ m}^{-2}$ and $v_h = 1100 \text{ m s}^{-1}$, (a5) $D = 0 \text{ mJ m}^{-2}$ and $v_h = 1200 \text{ m s}^{-1}$, (b1) $D = 1 \text{ mJ m}^{-2}$ and $v_h = 500 \text{ m s}^{-1}$, (b2) $D = 1 \text{ mJ m}^{-2}$ and $v_h = 900 \text{ m s}^{-1}$, (b3) $D = 1 \text{ mJ m}^{-2}$ and $v_h = 1050 \text{ m s}^{-1}$, (b4) $D = 1 \text{ mJ m}^{-2}$ and $v_h = 1100 \text{ m s}^{-1}$, (b5) $D = 1 \text{ mJ m}^{-2}$ and $v_h = 1200 \text{ m s}^{-1}$, (c1) $D = 2 \text{ mJ m}^{-2}$ and $v_h = 500 \text{ m s}^{-1}$, (c2) $D = 2 \text{ mJ m}^{-2}$ and $v_h = 900 \text{ m s}^{-1}$, (c3) $D = 2 \text{ mJ m}^{-2}$ and $v_h = 1050 \text{ m s}^{-1}$, (c4) $D = 2 \text{ mJ m}^{-2}$ and $v_h = 1100 \text{ m s}^{-1}$, (c5) $D = 2 \text{ mJ m}^{-2}$ and $v_h = 1200 \text{ m s}^{-1}$.

SW dispersion relation $\omega(k)$ can predict the Cherenkov excitation of SWs precisely with the presence of finite DMI.

Figure 5 shows the minimum velocity v_0 of the Spin-Cherenkov excitation for $D = 0 \text{ mJ m}^{-2}$, 1 mJ m^{-2} , 2 mJ m^{-2} and 3 mJ m^{-2} , as well as the corresponding dispersion relation. Only the branches of positive k are shown. The critical velocity for the SCE decreases linearly with increasing DMI in the investigated DMI range. As shown in the inset of Fig. 5, the dispersion relation for $D = 1 \text{ mJ m}^{-2}$ deviates from the case of $D = 0 \text{ mJ m}^{-2}$, resulting in a smaller critical velocity v_0 . $v_0 = 1000 \text{ m s}^{-1}$ for $D = 0 \text{ mJ m}^{-2}$ whereas $v_0 = 944 \text{ m s}^{-1}$ for $D = 1 \text{ mJ m}^{-2}$. The critical velocity further drops to 887 m s^{-1} as D increases to 2 mJ m^{-2} , indicating that the Cherenkov emission of SWs in permalloy strip with finite DMI can be excited more easily than the case of zero DMI. The SW dispersion relations without DMI ($D = 0 \text{ mJ m}^{-2}$) is a parabolic function of SW vector k when k is large^{9,13,29,30}. In Refs. 14 and 25, the SW dispersion relation is given analytically when DMI is included, indicating that the interfacial DMI results in the asymmetric dispersion. Such asymmetric dependence due to the interfacial DMI depends on the spin wave vector k and equilibrium magnetization distributions. Different with the typical Damon-Eshbach spin waves studied in Refs. 14 and 25, the SWs in our case propagate along the $\pm x$ -directions while the equilibrium magnetization is along the $+x$ -direction, corresponding to the back-volume mode. The SW dispersion is given by $\omega = \gamma_0 \sqrt{\omega_0^2 - (kD^*m_{z0})^2}$ when the DMI is considered. Here $D^* = \frac{2D}{\mu_0 M_S}$ and ω_0 is the

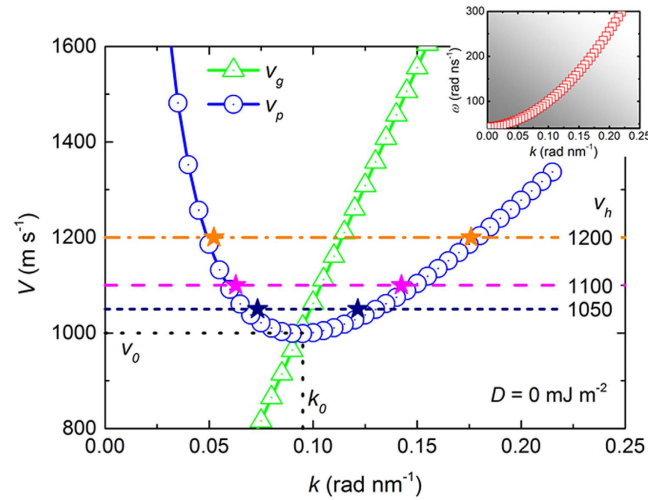


Figure 3. Numerically determined phase velocity $v_p(k)$ and group velocity $v_g(k)$ of SWs in the magnetic strip which is $12 \mu\text{m}$ long, 100 nm wide, and 10 nm thick as $D = 0 \text{ mJ m}^{-2}$. The value of $v_p(k)$ and $v_g(k)$ are extracted from the SW dispersion relation $\omega(k)$ shown in the inset. $v_p(k)$ has a minimum v_0 at k_0 , where the two curves $v_p(k)$ and $v_g(k)$ cross. The colored stars represent the wave vectors of the SW tails excited by the moving field pulse applied to the strip at the corresponding speed. The colored horizontal line, indicating the speed of the field pulse, connects the two SW branches.

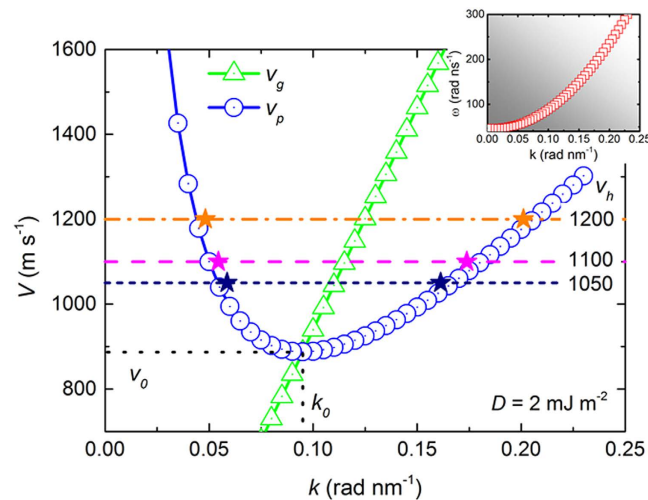


Figure 4. Numerically determined phase velocity $v_p(k)$ and group velocity $v_g(k)$ of SWs in the magnetic strip, with a length of $12 \mu\text{m}$, a width of 100 nm , and a thickness of 10 nm when $D = 2 \text{ mJ m}^{-2}$. The value of $v_p(k)$ and $v_g(k)$ are extracted from the SW dispersion relation $\omega(k)$ shown in the inset. $v_p(k)$ has a minimum v_0 at k_0 , where the curve $v_p(k)$ crosses the curve $v_g(k)$. The colored stars show the wave vectors of the SW tails excited by the moving field pulse applied to the strip at the corresponding speed. The colored horizontal line, indicating the speed of the field pulse, connects the two SW branches.

angular frequency in the absence of DMI. m_{z0} is the z -component of the magnetization. The SW dispersion relation remains symmetric, when the interfacial DMI is included. The SCE threshold can be calculated by $\frac{d\omega}{dk} = \frac{\omega}{k}$, which decreases with DMI⁹.

Discussions

The Cherenkov emission of spin waves has been numerically studied by considering the effect of DMI in permalloy strip. The resonant Spin-Cherenkov effect can be excited as the velocity of moving magnetic field pulse exceeds a certain threshold velocity. The Spin-Cherenkov effect threshold can be reduced in the presence of finite DMI. By further tuning the material parameters and geometries, resonant spin waves can be excited through Spin-Cherenkov effect at much lower threshold velocity of the moving dc field source. On the other hand, it is also feasible to increase the interaction region of the moving dc field source on the magnetic strip in real experiments. Indeed, we have investigated the Spin-Cherenkov effect with different sizes of the moving dc field source (see

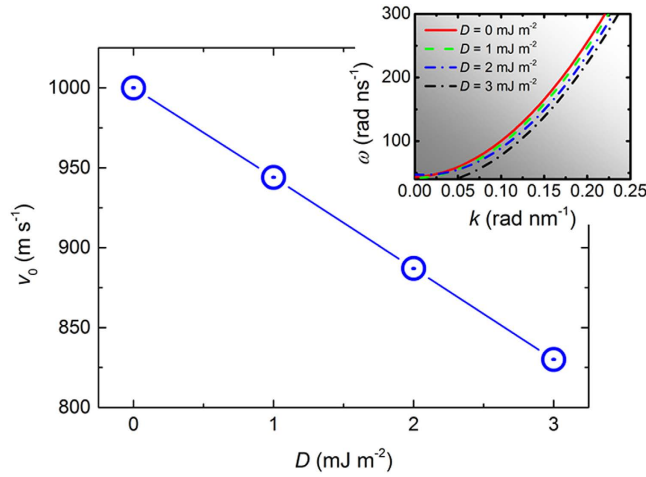


Figure 5. The minimum velocity v_0 for the Spin-Cherenkov excitation as $D = 0 \text{ mJ m}^{-2}$, 1 mJ m^{-2} , 2 mJ m^{-2} and 3 mJ m^{-2} . The insets shows the corresponding dispersion relations, which are obtained by applying a localized ac magnetic field and extracting the wavelength of the excited spin waves.

Supplementary Fig. 1), as well as with different thicknesses of the magnetic strip (see Supplementary Fig. 2). The Spin-Cherenkov effect in finite-DMI system might be interesting for fundamental physics and also promising for potential applications in spintronic and magnonic devices, easing the experimental complexity and difficulty of applying an external ac magnetic field or current for resonant SW excitations.

Methods

Modeling and simulation. The micromagnetic simulations are performed using the Object Oriented MicroMagnetic Framework (OOMMF) software including the interface-induced Dzyaloshinskii-Moriya interaction (DMI) extension module^{19–21,31–33}. The three-dimensional time-dependent magnetization dynamics is controlled by the Landau-Lifshitz-Gilbert (LLG) ordinary differential equation^{34–36}

$$\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_S} \left(\mathbf{M} \times \frac{d\mathbf{M}}{dt} \right), \quad (1)$$

where \mathbf{M} is the magnetization, \mathbf{H}_{eff} is the effective field, γ_0 is the Gilbert gyromagnetic ration, and α is the Gilbert damping coefficient. The effective field reads as follows

$$\mathbf{H}_{\text{eff}} = -\mu_0^{-1} \frac{\partial E}{\partial \mathbf{M}}. \quad (2)$$

The average energy density E as a function of \mathbf{M} is given by

$$E = A \left[\nabla \left(\frac{\mathbf{M}}{M_S} \right) \right]^2 - K \frac{(\mathbf{n} \cdot \mathbf{M})^2}{M_S^2} - \mu_0 \mathbf{M} \cdot \mathbf{H} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_d(\mathbf{M}) + E_{\text{DMI}}, \quad (3)$$

where A and K are the exchange and anisotropy energy constants, respectively. \mathbf{H} and $\mathbf{H}_d(\mathbf{M})$ are the applied and magnetostatic self-interaction fields while $M_S = |\mathbf{M}(\mathbf{r})|$ is the spontaneous magnetization. The E_{DMI} is the energy density of the interfacial DMI of the form^{21,31,36,37}

$$E_{\text{DMI}} = \frac{D}{M_S^2} \left(M_z \frac{\partial M_x}{\partial x} + M_z \frac{\partial M_y}{\partial y} - M_x \frac{\partial M_z}{\partial x} - M_y \frac{\partial M_z}{\partial y} \right), \quad (4)$$

where the M_x, M_y, M_z are the components of the magnetization \mathbf{M} and D is the interfacial DMI constant. The five terms at the right side of equation (3) correspond to the exchange energy, the anisotropy energy, the applied field (Zeeman) energy, the magnetostatic (demagnetization) energy and the interfacial DMI energy, respectively. The typical material parameters of permalloy, $\mu_0 M_S = 1 \text{ T}$, exchange constant $A = 1.3 \times 10^{-11} \text{ J m}^{-1}$, and zero anisotropy are adopted^{8,9,22,26}. Considering that the value of the effective interfacial DMI constant in the Py/Pt bilayers has been estimated to be within the range of $1.0\text{--}2.2 \text{ mJ m}^{-2}$ in Refs. 27 and 38, the interfacial DMI constant D is varied from 0 to 3 mJ m^{-2} in this paper. A rectangular shape field pulse is applied to $12\text{-}\mu\text{m}$ -long, 100-nm -wide, and 10-nm -thick magnetic strip with a magnitude of 10 mT in the $+z$ -direction and a 12 nm width in the x -direction, as shown in Fig. 1. The moving field pulse can be realized, for example, with a laser beam scanning over the surface of magnetic thin films³⁹. The results with different widths of the moving field pulse are shown in

Supplementary Fig. 1. The results with different thicknesses of the magnetic strip are shown in Supplementary Fig. 2. For simplicity, the uniform field along the film thickness is assumed. All samples are discretized into cells of $3 \text{ nm} \times 5 \text{ nm} \times 5 \text{ nm}$ in the simulation. Gilbert damping coefficient α is set to be 0.02 and the value for Gilbert gyromagnetic ratio γ_0 equals $2.211 \times 10^5 \text{ m A}^{-1} \text{ s}^{-1}$. Initially, the magnetization orients along the $+x$ -direction due to the shape anisotropy. The absorbing boundary condition has been implemented at both ends of the nano-strip, which effectively avoids the spurious spin wave reflections⁴⁰.

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Author Contributions

Y.Z. conceived the problem. Y.Z. and W.Z. coordinated the work. X.Z. carried out the numerical simulations. J.X. performed the theoretical analysis with the input from M.Y. All authors discussed the results and co-wrote the manuscript.

Additional Information

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