Accelerating, guiding, and compressing skyrmions by defect rails

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Magnetic skyrmions are promising candidates as information carriers in spintronic devices. The transport of individual skyrmions in a fast and controlled way is a key issue in this field. Here we introduce a novel platform for accelerating, guiding and compressing skyrmions along predefined paths. The guiding mechanism is based on two parallel defect-lines (rails), one attractive and the other repulsive. Numerical simulations, using parameters from state-of-the-art experiments, show that the speed of the skyrmions along the rails is increased up to a factor of ten with respect to the non-defect case whereas the distance between rails can be as small as the initial radius of the skyrmions. In this way, the flux of information that can be coded and transported with magnetic skyrmions could be significantly increased.

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Magneticskyrmions are being proposed as information carriers for a new generation of ultradense magnetic memories and logic devices [1]. In these systems, the presence/absence of a skyrmion usually codes the 1/0 bit of information. Due to their topological protection, relatively small deformations in the skyrmionic structure do not destroy the information. This fact, together with their small size (few tens of nanometers), can promote them as future building blocks for high-density magnetic transport and storage systems.

Racetracks with skyrmions driven by spin-polarized currents have been proposed to transport skyrmions [2]. In these systems, the racetrack borders create a confining potential [3, 4] that helps skyrmions to move along the track for electronic-spin densities below a given threshold, and avoiding the skyrmionic Hall effect because of the borders repulsion. The parallelization of transport using multichannel or several lanes for skyrmions [5, 6] could increase the flux of information that can be carried for a given total width. However, although the presence of one border can increase the velocity of the skyrmions close to that border [3, 7], their confinement between two borders decreases their velocity. In particular, as shown in Ref. [4], the narrower the track, the lesser the velocity of the skyrmions is along it.

Here we present an alternative concept for transporting skyrmions in films along a defined lane with increasing velocity as the lane becomes narrower, thus boosting the total flux of information that can be transported for a given width of material. To achieve this we take profit of the tunable effect that artificial defects can produce over skyrmions [8–10]. The central idea is to guide skyrmions along a lane defined by two parallel linear defects (rails), tailored in such a way that one of them is attractive and the other repulsive [10]. Under the adequate conditions, the skyrmion is channeled between the two defect lines and its speed is increased because the two rails thrust it in the same direction (sketch in Fig. 1). The optimum separation between rails is found to be as small as the radius of the skyrmion.

We model the system by considering a planar (xy-plane) ultrathin ferromagnetic film on top of a non-magnetic heavy metal substrate with strong spin-orbit coupling, providing interfacial Dzyaloshinskii-Moriya (iDM) interaction between the magnetic moments in the ferromagnet. The micromagnetic framework is used, where the magnetization distribution \( \mathbf{M} \) is has constant modulus \( M_s \) (the saturation magnetization) all over the ferromagnetic film. Once a skyrmion is created in the film, a spin-polarized current density \( \mathbf{J}_e \) flowing into the ferromagnet drives the skyrmion by the spin transfer torque (STT) given by

\[
\mathbf{T}_{STT} = (\mathbf{V}_e \cdot \nabla)\mathbf{M} - \frac{\beta}{M_s} (\mathbf{M} \times (\mathbf{V}_e \cdot \nabla)\mathbf{M}),
\]

where \( \mathbf{V}_e = \frac{\gamma P}{2e\mu_0 M_s} \mathbf{J}_e \), \( \gamma \) is the gyromagnetic ratio (\( \gamma = 2.21 \cdot 10^5 \text{ m A}^{-1} \text{ s}^{-1} \)), \( e \) the electron charge, \( \mu_0 \) the vacuum permeability, and \( P \) the spin polarization coefficient of electrical current. The main results of the present analysis would not change significantly for other possible driving scenarios [2] different from STT.

The system will be simulated by solving the micromagnetic Landau-Lifshitz-Gilbert equation [11]

\[
\frac{d\mathbf{m}}{d\tau} = -(\mathbf{m} \times \mathbf{h}_{\text{eff}}) + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{d\tau} + \mathbf{t}_{STT},
\]

where \( \alpha \) is the Gilbert damping constant, and all the length variables have been normalized to the exchange length, \( l_{\text{ex}} = \sqrt{2A/\mu_0 M_s^2} \) (\( A \) is the exchange constant), time \( \tau \) to \( \tau_0 = 1/\gamma M_s \), and magnetization and magnetic fields to \( M_s \).

**FIG. 1.** Sketch of the proposed skyrmionic rails. Two defect lines can guide the skyrmion driven by the spin-polarized current density \( \mathbf{J}_e \). When the skyrmion is channeled between the two defects, its speed can be increased.
$t_{STT}$ is the normalized spin-transfer torque, $t_{STT} = (t_0/M_s)\mathbf{T}_{STT}$ and $v_e = (t_0/l_{ex})\mathbf{v}_e$ is the normalized velocity of the driving-electrons. $h_{eff}$ is the normalized effective field that includes exchange, iDM, and uniaxial perpendicular anisotropy interactions,

$$h_{eff} = \nabla^2 \mathbf{m} + \xi[(\mathbf{v} \cdot \mathbf{m})\mathbf{z} - \nabla m_z] + \kappa m_z \mathbf{z},$$

where $\xi = D l_{ex}/A$ ($D$ is the iDM constant) and $\kappa = 2K/\mu_0M_s^2$ ($K$ is the uniaxial anisotropy constant) are dimensionless variables. Because ultrathin films are being considered, the demagnetizing fields are neglected in the calculations [8, 12, 13] (alternatively, one could consider an effective anisotropy constant that includes the demagnetizing effects [14, 15]). Typical values are used for the calculations: $M_s = 580$ $\text{kA/m}$, $A = 15$ $\text{pJ/m}$, $D = 3$ $\text{mJ/m}^2$, $K = 127$ $\text{kJ/m}^3$, and $\alpha = 0.1$ [1, 12, 16], so that $l_{ex} = 8.4$ nm, $t_0 = 7.8$ ps, $\xi = 1.68$, and $\kappa = 2.0$. Numerically, a $(40 \times 40)^2_{ex}$ calculation window with periodic boundary conditions and mesh cells of $(0.5 \times 0.5)^2 l_{ex}$ has been used.

In the simulations we proceed in the following way. Initially, a uniform magnetization state in the $-\mathbf{z}$ direction is considered. A skyrmion is generated by causing a distortion in the uniform background. The system evolves up to a given stationary skyrmionic state. With the parameters used the radius of the obtained skyrmions is $R \approx 2.5 l_{ex}$. Then, a spin-polarized electronic current flowing in the $x$-direction $\mathbf{v}_e = v_e \mathbf{x}$ is set up. It is known that, in the absence of defects or borders, the skyrmion moves in a straight line with velocity $\mathbf{v}_s$ and with a given angle with respect $\mathbf{v}_e$ (skyrmionic Hall effect) [17]. For simplicity, we consider that $\beta = \alpha$ so that the skyrmion moves initially in the $x$-direction with speed $v_s = v_e$. In this case, any deviation from this trajectory or any speed modification will be due to the presence of defects in the material. No qualitative differences have been found when considering $\beta \neq \alpha$.

We first consider a skyrmion approaching a single line defect. This rail is regarded as a straight line with modified iDM interaction (with respect to the rest of the sample). Micromagnetically, the value $\xi$ is changed into $\xi_d = \xi(1 + \delta)$, where $\delta$ indicates the strength of the defect. The values of $\delta$ range from $\delta = -1$ (total suppression of the local iDM interaction on the line) to $\delta = 1$ (doubling the local iDM interaction). $\delta < 0$ ($\delta > 0$) characterizes repulsive (attractive) defects [10]. The kind of defects necessary for creating these rails could be obtained by locally modifying the layer structure, by inserting wedges of heavy metal in the substrate, by atomic hydrogenation, by applying local electric fields, by changing locally the width of the layers, or, in general, by local variation in the chemical composition or mechanical distribution of atoms [18–21].

Our results show that depending on the driving velocity $v_e$ and the strength of the defect $\delta$, the skyrmion can be trapped, annihilated (by implosion), destabilized (by continuous deformation), or can go through the defect line. We show in Fig. 2a the calculated ($\delta, v_e$)-phase diagram for these different possibilities.

For weak defects ($\delta \sim 0$) the skyrmion goes through the defect. This region of crossing (region II in Fig. 2a) extends to larger $\delta$’s for larger velocities. When the velocity is high enough and/or when the defect is too strong (regions I and IV in Fig. 2a), other possibilities can appear. In particular, the skyrmion can vanish when approaching the repulsive defect line (Fig. 2b-I) or can be largely distorted and eventually destroyed when passing through a strong attractive defect (Fig. 2b-IV). These cases are not useful for guiding skyrmions and will not be studied in detail here. Nevertheless, the presence of these regions sets up the limiting parameters for an effective guiding of skyrmions without destroying them. Note that as a general fact, when the skyrmion approaches the attractive (repulsive) defect its radius increases (decreases).

There exists regions in the ($\delta, v_e$)-phase diagram (regions III.a and III.b in Fig. 2a) in which the skyrmion becomes trapped in the $x$ direction, but can move along the $y$ direction of the defect line. Interestingly, the skyrmion can be trapped both if the defect is repulsive (Fig. 2b-III.a, $\delta < 0$) or attractive (Fig. 2b-III.b, $\delta > 0$). However, an important difference appears between the two cases. For the attractive defect, the skyrmion goes through the defect before being guided along it, in the $+\mathbf{y}$ direction. But if the defect is repulsive, the skyrmion does not cross the defect line before being guided in the same direction $+\mathbf{y}$. Actually, if the skyrmion crossed a repulsive defect, it would escape.

As a result, within the adequate range of driving velocities, both opposite defects push the skyrmion along the same direction. The other important effect is that the speed of the skyrmion, when trapped and guided along the defect, increases with respect to the initial skyrmion speed. This is true for both repulsive and attractive defects.

All these results indicate that an optimum channel for skyrmions would be a combination of attractive-repulsive lines of defects. It is important that the skyrmion first reaches the attractive defect, goes through it and then finds the repulsive defect and does not cross it. In this arrangement, the skyrmion moves along the lane determined by the two rails and both cooperate in increasing the speed of the skyrmion. This is in contrast with the skyrmion moving on a track. There, both borders are repulsive and the skyrmion is accelerated when approaching to one border but decelerated when approaching the other [3, 7]. When the track becomes narrower and the skyrmion is affected by both borders no speed-up is expected, but a speed reduction instead [4].

We now study in detail the behavior of skyrmions when guided along rails formed by two defect-lines as a function of their separation $W$. The attractive and repulsive defect-lines are characterized by $\xi_+$ and $\xi_-$, respectively. To simplify the treatment and reduce the number of parameters we characterize both defect-lines by a single parameter:
FIG. 2. (a)($\delta$, $v_e$)-phase diagram for the different behaviors of skyrmion with a line-defect (see text). (b) Snapshots at different times (indicated in each figure in normalized units, the leftmost structure corresponds to $\tau_0$) of the skyrmionic structure [z-component of the magnetization: blue (red) color corresponds to magnetization pointing $-\hat{z}$ ($\hat{z}$), white to $m_z = 0$]. Each plot is calculated with the parameters indicated by dots in the phase diagram. The green vertical line represents the defect and the gray line the trajectory of the skyrmion. The length scale is identical in all plots and is indicated in units of $l_{ex}$ in the top-left plot.

$\xi_{\pm} = \xi(1 \pm \delta)$. Naturally, the use of different $\delta$’s for the different lines could result in a better optimization of the system. For the present study we have fixed $v_e = 0.018$ yielding $V_e = 19.4$ m/s, so that $J_e \simeq 5 \cdot 10^{11}$ A/m$^2$ ($P = 0.4$ is used), which are among typical values (Ref. [2]).

The final (non-normalized) velocity $V_f$ along the channel as a function of the separation between the two defect lines $W$ is shown in Fig. 3. The most remarkable fact is that, in clear contrast with the skyrmions on a track [4], the final speed of the guided skyrmions increases with decreasing $W$, as long as $W$ is larger than a certain optimum width $W_c$. The maximum $V_f$ is acquired when the width of the lane is $W_c$. By rising $\delta$, $W_c$ diminishes, and the maximum $V_f$ increases. Note however, that the value of $\delta$ cannot grow unlimitedly, since skyrmions would be no longer guided but destroyed by the defects themselves. The snapshots for the case $\delta = 0.6$ and $W = 2.5l_{ex} = 21$ nm are shown in Fig. 4, resulting in a final speed $V_f \simeq 190$ m/s for an initial speed of $V_i = V_e = 19.4$ m/s. That is, with a channel of
FIG. 3. Velocity along the rails, $V_f$, as a function of the separation $W$ between them. The different lines correspond to different values of $\delta$. The vertical and horizontal dashed lines are shown for comparison and indicate the initial diameter and velocity of the skyrmion, respectively. The encircled point is the one used for the snapshots in Fig. 4.

FIG. 4. Snapshots of the skyrmion channeled between two defect lines at different times indicated in the figure (in normalized units, the leftmost structure corresponds to $\tau_0$). The length scale is indicated in units of $l_{ex}$. Green (pink) vertical lines indicate the attractive (repulsive) defect line. The gray line is the trajectory of the skyrmion. Note the boosting in the velocity since the intervals between consecutive snapshots are not identical. The parameters used are those corresponding to the encircled value of Fig. 3: $\delta = 0.6$, $W/l_{ex} = 2.5$, $v_e = 0.018$.

a width of the order of the initial radius of the skyrmion ($R \approx 21$ nm), the skyrmion can be efficiently guided while its speed is increased by one order of magnitude when moving on the rails.

The skyrmions are compressed and slightly deformed (they have elliptical shape) when guided along the rails with width close to the optimum one, but this fact would not compromise the carried information because the topological structure would not be destroyed. The factor-of-ten boosting in the speed could be maintained (or even increased) using larger current densities, although at the price of increasing the $\delta$ factor of the defects. An alternative result is that with the use of rails, a given velocity for skyrmions can be achieved with a factor-of-ten less current density than without using them. One can also envisage parallelization of rails tuning adequately the strength of the defects. Being guided, accelerated and compressed, the amount of skyrmionic information that can be transported for the total width of the film could be boosted.

To conclude, we have presented a novel platform for accelerating skyrmions along guiding rails. The rails consist in a pair of line defects, one of them attractive (local increase of iDM interaction) and the other repulsive (local reduction
of iDM interaction). Within a range of driving current densities and strengths of the defects, the skyrmion is guided along channels with a width of the order of the radius of the free skyrmion whereas its speed is enhanced by an order of magnitude. The use of skyrmions as carriers of information will need the feasible control of writing, transporting, storing, and reading individual skyrmions in a fast, dense, and controllable way. The present work provides a new strategy for enhancing the transport stage.

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