AIP Journal of Applied Physics

Indirect switching of vortex polarity through magnetic dynamic coupling

G. B. M. Fior, E. R. P. Novais, J. P. Sinnecker, A. P. Guimarães, and F. Garcia

Citation: Journal of Applied Physics **119**, 093906 (2016); doi: 10.1063/1.4942534
View online: http://dx.doi.org/10.1063/1.4942534
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/119/9?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS 119, 093906 (2016)

Indirect switching of vortex polarity through magnetic dynamic coupling

G. B. M. Fior,[1] E. R. P. Novais,[2,a)] J. P. Sinnecker,[2] A. P. Guimarães,[2] and F. Garcia[2]
[1]Laboratório Nacional de Luz Síncrotron, 13083-970 Campinas, São Paulo , Brazil
[2]Centro Brasileiro de Pesquisas Físicas, 22290-180 Rio de Janeiro, Rio de Janeiro, Brazil

(Received 29 October 2015; accepted 10 February 2016; published online 2 March 2016)

Magnetic vortex cores exhibit a gyrotropic motion and may reach a critical velocity, at which point they invert their z-component of the magnetization. We performed micromagnetic simulations to describe this vortex core polarity reversal in magnetic nanodisks with a perpendicular anisotropy. We found that the critical velocity decreases with the increase in perpendicular anisotropy, therefore departing from a universal criterion that relates this velocity only to the exchange stiffness of the material. This leads to a critical velocity inversely proportional to the vortex core radius. We have also shown that in a pair of interacting disks, it is possible to switch the core vortex polarity through a non-local excitation; exciting one disk by applying a rotating magnetic field, one is able to switch the polarity of a neighbor disk, with a larger perpendicular anisotropy.
[http://dx.doi.org/10.1063/1.4942534]

I. INTRODUCTION

In recent years, a great deal of interest has been given to low-dimensional magnetic systems, in particular, systems with magnetic vortices found in their equilibrium magnetic configuration.[1–4] The vortices are characterized by presenting curling magnetization in the plane—the curling direction defines the circulation: $c = +1$ (counterclockwise (CCW)) or -1 (clockwise (CW)). In the center of the structure—the vortex core—the magnetization points out of the plane, up or down, defining the polarity p ($p = +1$ or $p = -1$). The core is surrounded by a circular region of opposite magnetization (dip). The core radius, as well as other properties, can be tailored by varying the perpendicular magnetic anisotropy of the nanostructures.[5–7]

The dynamic behavior of the magnetic vortices has been extensively studied.[8–12] When the vortex core is displaced from the equilibrium position, two relevant consequences are the asymmetry of the dip and the appearance of a restoring force. This force is responsible for the motion—gyrotropic motion—toward the disk center. This motion has a direction that depends on the polarity, i.e., it is CW for $p = +1$ and CCW for $p = -1$, and its eigenfrequency depends on the ratio of the thickness to the radius of the disk $\beta = L/R$. For small thickness disks, $\nu_0 = \omega_0/2\pi \propto M_s\,\beta$,[13] where M_s is the saturation magnetization of the disk material. However, the influence of uniaxial perpendicular anisotropy on the dynamics of vortex cores has not been extensively investigated so far.

Among the dynamic properties studied, the switching of vortex cores' polarity has deserved special attention in the literature. For example, the polarity can be inverted through several methods, which include the application of pulsed in-plane fields and polarized spin currents, among others.[8,9,14–18] It has been observed that the rotating magnetic fields at the resonance frequency (ν_0) are particularly effective in performing this inversion; this arises from the fact that after switching, the rotating field is no longer in resonance, due to the dependence of the vortex core rotation direction on the polarity p.[9]

Some proposed applications for vortex cores involve the interaction between side by side vortices, as, for example, the vortex-based transistor.[19] Two disks with magnetic vortices in the ground state configuration interact very weakly, since they present magnetic flux closure. However, a vortex core performing a gyrotropic motion generates sufficient magnetostatic energy to dynamically couple to a neighbor vortex, as demonstrated in some recent studies.[12,20–26] Particularly interesting is the fact that it is possible to transfer energy, with negligible loss between two neighbor vortices by stimulated gyrotropic motion.[23] This coupling is strongly dependent on the distance d between the centers of the vortices and on their relative polarities.[12,26–28]

The aim of this work is to demonstrate that, using micromagnetic simulation, it is possible to switch remotely the polarity of a given vortex, through a non-local excitation of a neighbor vortex; this was reached by suitably combining the perpendicular magnetic anisotropies of the nanostructures. In order to achieve this goal, we initially investigated the influence of the uniaxial perpendicular magnetic anisotropy (K_z) on the dynamic properties of isolated disks, particularly the switching of the vortex core, induced by a rotating magnetic field in the plane of the disk. We showed that the eigenfrequency, the velocity (critical velocity v_{crit}) of the core immediately before polarity reversal, as well as its distance (critical distance r_{crit}) from the center, depend on the magnitude of this K_z.

All micromagnetic simulations were carried out using the freely available software OOMMF,[29] employing permalloy disks with diameter $D = 500$ nm and thickness $L = 20$ nm. The magnetic parameters are $M_s = 860$ kA/m for the saturation magnetization, the exchange stiffness is $A = 13$ pJ/m, and the Gilbert damping is $\alpha = 0.01$. Following most authors of the cited works, we used a cell size of $5 \times 5 \times 5\,\mathrm{nm}^3$. The physical argument for this choice is that each dimension of the cell should be comparable or smaller than the exchange

[a)]Present address: Instituto de Física, Universidade Federal de Alagoas, 57072-970 Maceió, AL, Brazil.

length of the simulated material (∼5 nm for permalloy). However, we have made some simulations with different cell sizes: the computed critical velocities depend on the cell sizes, but the phenomenon is essentially the same. We varied the perpendicular anisotropies from $K_z = 0$ to 237 kJ/m^3; beyond this upper limit, the vortex structure is no longer stable for the disk dimension studied, and a skyrmion configuration is the state of minimum energy.[5,6]

II. REVERSAL OF THE VORTEX POLARITY OF A SINGLE DISK AS A FUNCTION OF K_z

To study the switching of a vortex core induced by another vortex driven by a resonant rotating magnetic field, initially we had to investigate the properties of individual vortices as a function of K_z. As we had previously demonstrated,[5–7] the vortex core is very sensitive to the magnitude of K_z, i.e., the larger it is, the larger will be the vortex core radius: $R_c = \sqrt{2A/\mu_0 M_s^2 - 2K_z}$. This dependence is represented on the right-hand axis in Fig. 1.

We obtained ν_0 as a function of the value of K_z by observing the relaxation motion of a vortex (excited by a static field) toward the equilibrium position, once the field is switched off. The dependence of this frequency on K_z is given by the left-hand axis in Fig. 1; with increasing anisotropy, ν_0 falls by some 3% in the range of K_z studied. The fact that this range is relatively narrow is relevant for the study conducted with the pair of vortices: a study of the excitation of a vortex by a rotating magnetic field demonstrated that this field was effective in a frequency range of about 6%.[30]

When a vortex core is removed from the center equilibrium position by a rotating planar field with a frequency close to ν_0, it moves away from the center in a spiral motion: as we mentioned above, this is an especially efficient method to excite the vortex.[9] The tangential core velocity will increase as the core moves away from the center. Above a certain threshold field amplitude B_{thres}, it will reach a critical velocity value v_{crit} at which the polarization is reversed.[31–33] It has been demonstrated that above this threshold, the distance $r_{\text{crit}} = v_{\text{crit}}/2\pi\nu_0(K_z)$ from the center where the inversion of the vortex core occurs is independent of the field amplitude.[8,9,34] On the other hand, for amplitudes below or equal to B_{thres}, the vortex core reaches a stationary orbit, i.e., it does not switch polarity.

We illustrate the independence of the critical velocity on the field amplitude in Fig. 2 that shows the time evolution of the vortex core distance from the center, for several rotating field amplitudes, at frequency ν_0 ($K_z = 100$ kJ/m^3). The sudden drop in the curves occur at r_{crit}; after the inversion, the core motion changes direction and begins to turn in a direction opposite to the rotating magnetic field, therefore leaving the resonance condition. The core then relaxes toward the center of the disk. We also observe that r_{crit} is the same for all field amplitudes, but for larger amplitudes, as expected, the vortex core reaches this radius earlier.

Magnetic rotating fields with the gyrotropic frequencies $\nu_0(K_z)$ were used to excite the disk with a given K_z. For each value of K_z, the simulation resulted in a different critical velocity and radius, as shown in Fig. 3. It is worth noting that all the curves in Fig. 3 coincide below v_{crit}, independently of the value of the anisotropy, i.e., the radial component of the core velocity is the same, independent of K_z. It is clear from Fig. 3 that by including a K_z term, the radial distance traveled by the vortex core before reversing the polarity is smaller for larger K_z. Thus, a magnetic system with K_z has a critical radius smaller than the system without anisotropy. On analyzing Fig. 3, we can obtain the critical radius as a function of K_z. The radius r_{crit} decreases approximately 50 nm (about 35%) with the increase in K_z from zero to 237 kJ/m^3.

Several authors have addressed the problem of dynamic switching of vortex core polarity. Lee *et al.*[34] proposed a universal criterion for the critical velocity; these authors have considered that the critical velocity v_{crit} (and also r_{crit}) depends only on the intrinsic parameter of the magnetic material, namely, the exchange stiffness A: $v_{\text{crit}} \cong 1.66\gamma\sqrt{A}$, where γ is the gyromagnetic ratio.

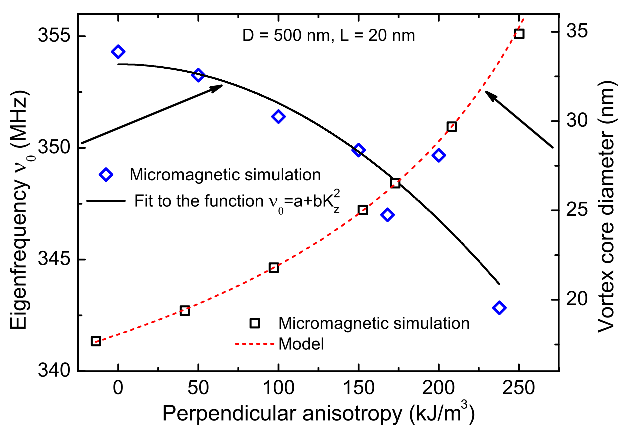

FIG. 1. Dependence of the vortex eigenfrequency ν_0 on the perpendicular anisotropy K_z, for a disk of diameter $D = 500$ nm and thickness $L = 20$ nm (blue diamonds, left-hand scale); the line is a fit to the function $\nu_0 = a + bK_z^2$. The dependence of the vortex core diameter on the perpendicular anisotropy (black squares, right-hand scale) is also shown; the dotted line is given by the model in Ref. 5.

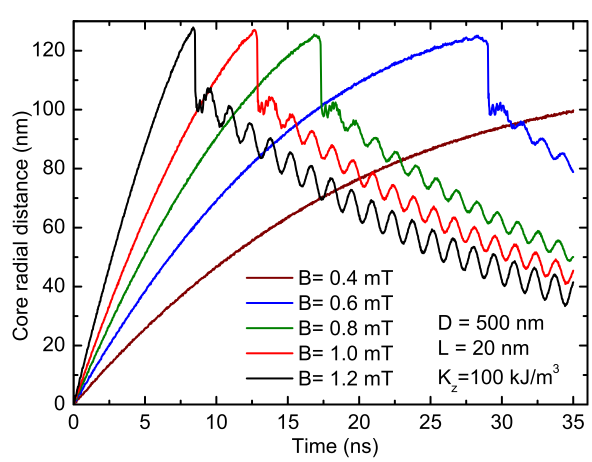

FIG. 2. Temporal evolution of the vortex core distance from the center of the disk, for several rotating magnetic field amplitudes, for a disk of diameter $D = 500$ nm, thickness $L = 20$ nm, and anisotropy constant $K_z = 100$ kJ/m^3.

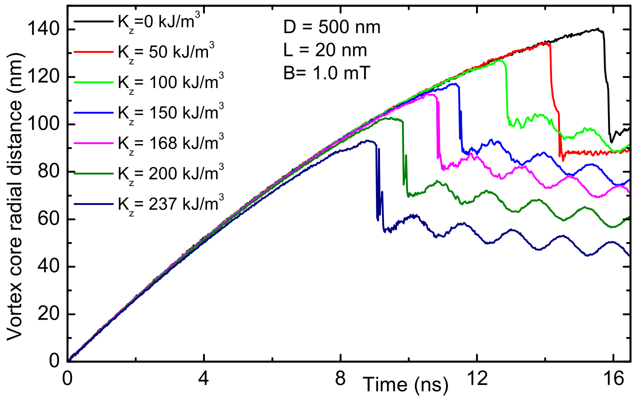

FIG. 3. Temporal evolution of the distance between the vortex core and the center of the disk, for field amplitude $B = 1$ mT, for a disk of diameter $D = 500$ nm and thickness $L = 20$ nm, and different values of the perpendicular anisotropy constant K_z.

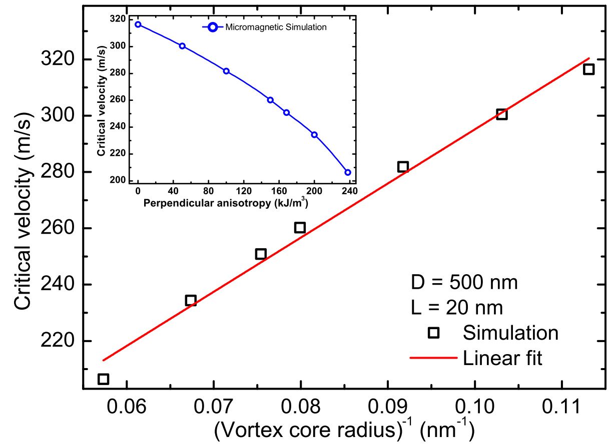

FIG. 5. Relation between the vortex core critical velocity (v_{crit}) and the inverse of the core radius R_c^{-1} for a disk of diameter $D = 500$ nm and thickness $L = 20$ nm, varying the perpendicular anisotropy. The red continuous line is a linear fit of the form $v_{crit} \propto R_c^{-1}$.

Guslienko *et al.*[31] have explained the switching of the vortex core as due to the gyrofield that is proportional to the core velocity. This field has a direction opposite to the core polarity, thus promoting the asymmetric increase in the dip. At the critical velocity, the dip magnetization becomes equal to $m_z = -1$, and the vortex core switches (see Fig. 4). Later, Khvalkovskiy *et al.*[35] studied how the critical velocity is affected by a perpendicular magnetic field. These authors confirmed that the critical velocity is proportional to the radius of the vortex core, i.e., $v_{crit} \approx \gamma R_c$, as proposed earlier.[31]

Analogously, we varied the perpendicular anisotropy, in order to modify the core size, and finally study its effect on the critical velocity. These results are presented in Figure 5. The red continuous line represents the behavior of v_{crit} as a function of R_c, showing that v_{crit} is roughly proportional to $1/R_c$. In the inset of Fig. 5, the dependence of the critical velocity on K_z is presented.

At a first glance, our results disagree with those found by Guslienko *et al.*[31] and Khvalkovskiy *et al.*[35] However, it is worth noting that, while the perpendicular magnetic field acts differently on the core and on the dip, i.e., increasing one will necessarily decrease the other, on the other hand, K_z favors the increase in both core and dip, since K_z is uniaxial. This may be the cause of the opposite dependence on the critical velocity.

Therefore, we could conclude that the effect of K_z on the vortex core dynamics has a dominant role if compared to other aspects, such as the core size. However, the details of the dependence of the vortex core dynamics on K_z are beyond the scope of the present work.

III. REMOTE REVERSAL OF THE CORE POLARITY

The dynamically induced magnetic interaction between spatially separated magnetic nanodisks has been studied in some previous works.[23,25,26,36] In the present work, we have used this same coupling to study the possibility of remote core polarity reversal in a pair of magnetic disks. In order to achieve this goal, our strategy was to excite, by applying a rotating magnetic field, just one of the disks. We chose the field amplitude, in such a way, to be just below the threshold of vortex core polarity reversal, ensuring a stationary core orbit with the largest possible radius, for a given anisotropy. We expected to induce the remote core reversal of the second disk (through dynamic magnetic coupling only) in the case where the critical radius (r_{crit}) of this disk is smaller than r_{crit} of the first one. As we have shown above, for a single disk, the r_{crit} (as well as the critical velocity) depends inversely on the value of the perpendicular anisotropy, r_{crit} presenting its largest value for $K_z = 0$. Therefore, in one disk of the pair (disk 1), K_z was always kept constant and equal to zero ($K_z = 0$), in order to reach the maximum possible orbit. On the other hand, we changed K_z (from $K_z = 0$ to 237 kJ/m^3) of the other disk (disk 2). It is important to emphasize that only one disk of the pair (disk 1) was excited with the rotating magnetic field, the other (disk 2) being totally passive.

In our simulations, both disks have the same diameter, $D = 500$ nm, and the same thickness, $L = 20$ nm. The distance between the centers of the disks was maintained the same for all cases, $d = 550$ nm (Fig. 6(a)). We observed that a pair of

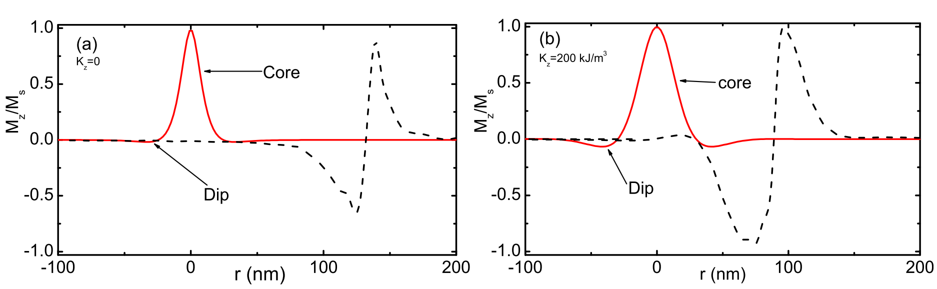

FIG. 4. Profile of the vortex core in equilibrium (continuous red line) and immediately before switching (dashed black line), showing the development of the dip, for (a) $K_z = 0$ and (b) $K_z = 200$ kJ/m^3.

disks with the same polarity ($p_1p_2 = 1$) has a weaker coupling than the pair with opposite polarity ($p_1p_2 = -1$). Also, the circulation of the disks is irrelevant for the coupling. These findings are consistent with previous results.[12,23–28]

As expected, in a pair of disks characterized by any combination of circulations and polarities separated by a distance $d = 550$ nm and with the same K_z, we observed that, by exciting only one disk, the amplitude of the oscillatory motion is approximately the same for both disks, with a phase difference. An energy transfer between the two disks was evident. On the other hand, when we introduced K_z on disk 2, we could distinguish between two distinct behaviors, depending on the relative polarities of the disks. With $p_1p_2 = -1$, we could observe the switching of polarity of disk 2, purely induced by the movement of disk 1, which creates a magnetic coupling between them, as we can see in Figs. 6(b) and 6(c). The polarity reversal only takes place due to the fact that the critical radius of disk 2 is smaller than the radius for $K_z = 0$; therefore, disk 2 is able to reach the critical condition, and then switch. In the case of $p_1p_2 = +1$, since the coupling is weaker, the transferred energy rate is smaller, and in our simulations, we have observed that it is more difficult to switch disk 2.

Following this idea, we have been able to reverse indirectly the polarity of a vortex core, as shown in Fig. 7. Disk 1, with $K_z = 0$ (in Fig. 7(a)), was excited with a given rotating field amplitude, with the frequency $\nu_0 = 355$ MHz, while for disk 2, the K_z was varied. The discontinuities in the radial distance of the core of disk 2 characterize the moments when the core inverts. We see that the reversal occurs for disk 2, although the polarity of the excited disk is maintained. Disk 2 (see Fig. 7(b)) has not been excited by the rotating field, but the stray field from disk 1 induces the switching of its core polarity.

In Fig. 3, one could see that the radial distance of the vortex cores for a single disk before inversion shows the same time dependence, independently of the value of K_z. The same is true for the radial distance of the core in disk 1 and disk 2 in the interacting pair of disks, as shown in Fig. 7. The shape of the curve, however, is modified in relation to the case of one single disk, as the motion of the vortex in disk 1 affects the motion in disk 2, and vice-versa.

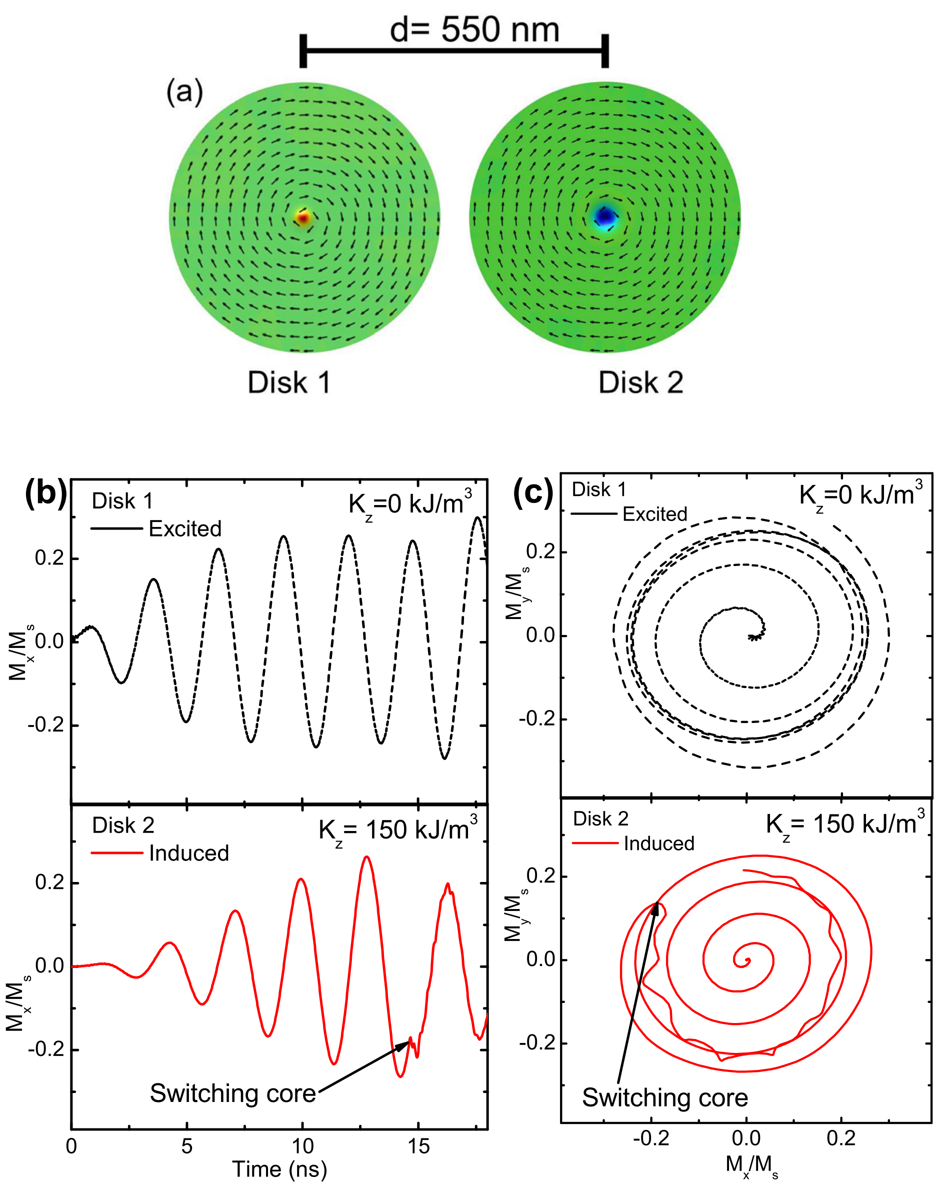

FIG. 6. In (a), scheme a pair of disks with different perpendicular anisotropies, $p_1p_2 = -1$. In (b), we show that M_x of the excited disk 1 (black dashed line) has the same amplitude M_x as disk 2 (red solid line) induced by the motion of disk 1. In (c), we show the gyrotropic motion for the excited disk (black dashed line) and the inversion of the motion of the core in disk 2 (red solid line), due to the inversion of its polarity.

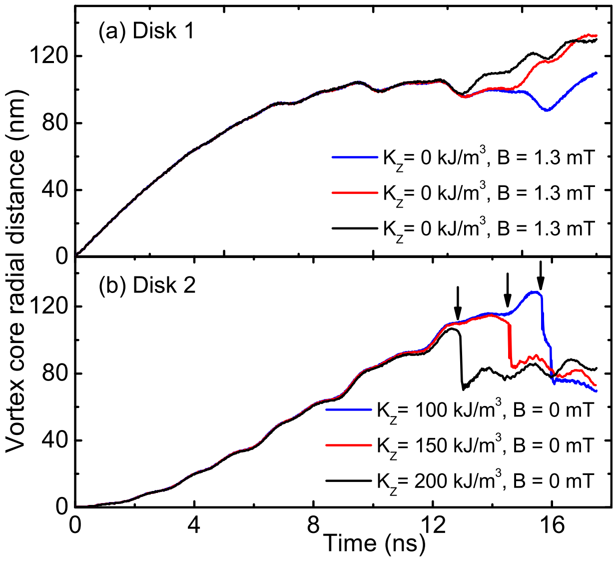

FIG. 7. Radial distance traveled by the vortex cores in the system of two disks. In (a), disk 1, with $K_z = 0$, with applied rotating magnetic fields of different amplitudes; (b) disk 2, with $K_z = 200\,\mathrm{kJ/m^3}$ and no applied rotating field. The discontinuities in the curves, indicated by the arrows, show where there was a polarity change.

The fact that one "master disk" can be used to tune the polarity of the neighboring disks, without altering its own polarity, is relevant for future applications. This disk would have $K_z = 0$, and the other would have different values for K_z, so that, if we employ $B = 1.3\,\mathrm{mT}$, for 14 ns, for instance, only disks with $K_z = 200\,\mathrm{kJ/m^3}$ or larger would reverse their polarity. If B is applied for 15 ns, disks of K_z up to $150\,\mathrm{kJ/m^3}$ would invert. We could therefore create an array of disks with different states of memory. Exciting disk 1 with a constant eigenfrequency ν_0 and different elapsed times, one could selectively switch neighbor disks with different anisotropies.

IV. CONCLUSIONS

In summary, in this study, we explored the influence of a perpendicular anisotropy on the vortex core polarity reversal in two systems: single disk and pair of interacting disks. In the case of a single disk, we observed that the natural frequency of the vortex motion is changed in the presence of a K_z. We applied a rotating magnetic field with a frequency corresponding to the motion in the presence of K_z and measured the critical reversal velocity. We showed that the critical velocity decreases with the increase in K_z, or with the increase in the vortex core radius. The critical velocity is inversely proportional to the vortex core radius: $v_{\mathrm{crit}} \propto 1/R_{\mathrm{c}}$ (K_z) for disks with $K_z \neq 0$, therefore departing from a universal dependence given as $v_{crit} \cong 1.66\gamma\sqrt{A}$ in the literature.[34]

In a pair of disks with different K_z, their natural frequencies are also different. By exciting only the disk with $K_z = 0$ on its natural frequency and varying the field amplitude, the gyrotropic motion of one vortex induces a similar motion on the other. For a pair of disks with different K_z, we can find a configuration such that we may reverse the polarity of the second disk before reversing the polarity of the disk being excited by the rotating magnetic field. This indirect, or induced, polarity reversal may be used in magnetic vortex applications, such as vortex magnetic memories.

ACKNOWLEDGMENTS

The authors would like to thank the Brazilian agencies CNPq, FAPERJ, FAPESP, and CAPES.

[1]A. P. Guimarães, *Principles of Nanomagnetism* (Springer, Berlin, 2009).
[2]T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science **289**, 930 (2000).
[3]R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. **83**, 1042 (1999).
[4]C. L. Chien, F. Q. Zhu, and J.-G. Zhu, Phys. Today **60**(6), 40 (2007).
[5]F. Garcia, H. Westfahl, J. Schoenmaker, E. J. Carvalho, A. D. Santos, M. Pojar, A. C. Seabra, R. Belkhou, A. Bendounan, E. R. P. Novais, and A. P. Guimarães, Appl. Phys. Lett. **97**, 022501 (2010).
[6]E. R. P. Novais, P. Landeros, A. G. S. Barbosa, M. D. Martins, F. Garcia, and A. P. Guimarães, J. Appl. Phys. **110**, 053917 (2011).
[7]E. R. P. Novais, S. Allende, D. Altbir, P. Landeros, F. Garcia, and A. P. Guimarães, J. Appl. Phys. **114**, 153905 (2013).
[8]K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Ono, A. Thiaville, and T. Ono, Nat. Mater. **6**, 269–273 (2007).
[9]S.-K. Kim, K.-S. Lee, Y.-S. Yu, and Y.-S. Choi, Appl. Phys. Lett. **92**, 022509 (2008).
[10]S. Bohlens, B. Krüger, A. Drews, M. Bolte, G. Meier, and D. Pfannkuche, Appl. Phys. Lett. **93**, 142508 (2008).
[11]A. Ruotolo, V. Cros, B. Georges, A. Dussaux, J. Grollier, C. Deranlot, R. Guillemet, K. Bouzehouane, S. Fusil, and A. Fert, Nat. Nanotechnol. **4**, 528 (2009).
[12]F. Garcia, J. P. Sinnecker, E. R. P. Novais, and A. P. Guimarães, J. Appl. Phys. **112**, 113911 (2012).
[13]K. Y. Guslienko, X. F. Han, D. J. Keavney, R. Divan, and S. D. Bader, Phys. Rev. Lett. **96**, 067205 (2006).
[14]B. V. Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fähnle, H. Brückl, K. Rott, G. Reiss, I. Neudecker, D. Weiss, C. H. Back, and G. Schütz, Nature **444**, 461 (2006).
[15]K.-S. Lee and S.-K. Kim, Appl. Phys. Lett. **91**, 132511 (2007).
[16]K.-S. Lee, Y.-S. Yu, Y.-S. Choi, D.-E. Jeong, and S.-K. Kim, Appl. Phys. Lett. **92**, 192513 (2008).
[17]G. de Loubens, A. Riegler, B. Pigeau, F. Lochner, F. Boust, K. Y. Guslienko, H. Hurdequint, L. W. Molenkamp, G. Schmidt, A. N. Slavin, V. S. Tiberkevich, N. Vukadinovic, and O. Klein, Phys. Rev. Lett. **102**, 177602 (2009).
[18]P. Wohlhuter, M. T. Bryan, P. Warnicke, S. Gliga, S. E. Stevenson, G. Heldt, L. Saharan, A. K. Suszka, C. Moutafis, R. V. Chopdekar, J. Raabe, T. Thomson, G. Hrkac, and L. J. Heyderman, Nat. Commun. **6**, 7836 (2015).
[19]D. Kumar, S. Barman, and A. Barman, Sci. Rep. **4**, 4108 (2014).
[20]B. L. Mesler, P. Fischer, W. Chao, E. H. Anderson, and D.-H. Kim, J. Vac. Sci. Technol., B **25**, 2598 (2007).
[21]L. Bocklage, B. Krüger, R. Eiselt, M. Bolte, P. Fischer, and G. Meier, Phys. Rev. B **78**, 180405 (2008).
[22]Y. Liu, Z. Hou, S. Gliga, and R. Hertel, Phys. Rev. B **79**, 104435 (2009).
[23]A. Vogel, A. Drews, T. Kamionka, M. Bolte, and G. Meier, Phys. Rev. Lett. **105**, 037201 (2010).
[24]S. Sugimoto, Y. Fukuma, S. Kasai, T. Kimura, A. Barman, and Y. C. Otani, Phys. Rev. Lett. **106**, 197203 (2011).
[25]H. Jung, K.-S. Lee, D.-E. Jeong, Y.-S. Choi, Y.-S. Yu, D.-S. Han, A. Vogel, L. Bocklage, G. Meier, M.-Y. Im, P. Fischer, and S.-K. Kim, Sci. Rep. **1**, 59 (2011).
[26]O. V. Sukhostavets, J. González, and K. Y. Guslienko, Phys. Rev. B **87**, 094402 (2013).
[27]A. Vogel, T. Kamionka, M. Martens, A. Drews, K. W. Chou, T. Tyliszczak, H. Stoll, B. Van Waeyenberge, and G. Meier, Phys. Rev. Lett. **106**, 137201 (2011).
[28]J. P. Sinnecker, H. Vigo-Cotrina, F. Garcia, E. R. P. Novais, and A. P. Guimarães, J. Appl. Phys. **115**, 203902 (2014).
[29]M. Donahue and D. Porter, "Object oriented micromagnetic framework (OOMMF)" (1999).
[30]S.-K. Kim, Y.-S. Choi, K.-S. Lee, K. Y. Guslienko, and D.-E. Jeong, Appl. Phys. Lett. **91**, 082506 (2007).

[31]K. Y. Guslienko, K.-S. Lee, and S.-K. Kim, Phys. Rev. Lett. **100**, 027203 (2008).
[32]M. Curcic, B. Van Waeyenberge, A. Vansteenkiste, M. Weigand, V. Sackmann, H. Stoll, M. Fähnle, T. Tyliszczak, G. Woltersdorf, C. H. Back, and G. Schütz, Phys. Rev. Lett. **101**, 197204 (2008).
[33]X. M. Cheng, K. S. Buchanan, R. Divan, K. Y. Guslienko, and D. J. Keavney, Phys. Rev. B **79**, 172411 (2009).
[34]K.-S. Lee, S.-K. Kim, Y.-S. Yu, Y.-S. Choi, K. Y. Guslienko, H. Jung, and P. Fischer, Phys. Rev. Lett. **101**, 267206 (2008).
[35]A. V. Khvalkovskiy, A. N. Slavin, J. Grollier, K. A. Zvezdin, and K. Y. Guslienko, Appl. Phys. Lett. **96**, 022504 (2010).
[36]H. Jung, Y.-S. Yu, K.-S. Lee, M.-Y. Im, P. Fischer, L. Bocklage, A. Vogel, M. Bolte, G. Meier, and S.-K. Kim, Appl. Phys. Lett. **97**, 222502 (2010).