Controlled propagation of locally excited vortex dynamics in linear nanomagnet arrays

This article has been downloaded from IOPscience. Please scroll down to see the full text article.


(http://iopscience.iop.org/0022-3727/43/33/335001)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 59.160.210.68
The article was downloaded on 05/08/2010 at 14:15

Please note that terms and conditions apply.
Controlled propagation of locally excited vortex dynamics in linear nanomagnet arrays

Saswati Barman\(^1\), Anjan Barman\(^1,2,4\) and Y Otani\(^2,3\)

\(^1\) Department of Material Sciences and Unit for Nanoscience and Technology, S. N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700098, India
\(^2\) RIKEN ASI, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
\(^3\) Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

E-mail: abarman@bose.res.in

Received 29 March 2010, in final form 9 July 2010
Published 3 August 2010
Online at stacks.iop.org/JPhysD/43/335001

Abstract

The ability to propagate local electromagnetic excitation in a medium with spatially modulated physical properties is important for fundamental science and also for applications in photonic, phononic and magnonic crystals. Here, we present a controlled propagation of locally excited magnetic vortex dynamics through a linear array of nanomagnetic discs by controlling the polarization, chirality and shape of the discs. The control is based upon the magnetostatic interaction between the nanodiscs, mediated by the magnetic side charges generated by the gyrating vortices. The magnitude and sign of the side charges and their separation depend strongly on the magnetic ground states of the vortices, including the core polarization and the chirality. We find that the transmission of peak amplitude and velocity of propagation of the excitation along the array is optimized for identical core polarization and chirality of the nanodiscs with geometric asymmetry. More than seven times increase in the transmitted amplitude is observed in the optimized structure as opposed to the non-optimized structure, which is also found to be robust to defects.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ordered arrays of magnetic nanostructures are extremely important from the fundamental and application points of view. Potential applications are the novel patterned recording media [1], magnetic random access memory [2] and magnetic logic devices [3, 4]. Magnetization dynamics of single and arrays of nanomagnets of different shapes and sizes have been explored recently [5–9], due to their potential applications in high speed magnetic data storage and magnetic logic devices. In particular, the magnetic vortex structure has received considerable attention because of its stable flux closure configuration. It is a potential candidate for high density magnetic data storage and logic devices because of its magnetic stability in the remanent state [10, 11]. For a particular range of dimension of cylindrical magnetic nanodiscs, a stable magnetic vortex is energetically favoured. The flux closure structure is characterized by an in-plane clockwise (CW) or counterclockwise (CCW) circulating magnetization, defined as chirality \(C\). To avoid a singularity at the centre, magnetization becomes perpendicular to the disc plane, defined as polarization \(p\) (\(p = \pm 1\)). Static and dynamic magnetic properties of single magnetic vortex, such as its internal spin structure, nucleation and annihilation of vortex [12, 13], and gyrotropic motion and switching of the vortex core [14–17] by magnetic field or spin polarized current, have received considerable attention. When the discs are arranged into one- or two-dimensional arrays, the inter-disc magnetostatic interaction is small in the absence of an external magnetic field. However, upon application of a dc...
or pulsed magnetic field or spin polarized current, the inter-disc magnetostatic interaction becomes significant, due to the appearance of magnetic side charges, which increases with decreasing inter-disc distance [18].

A control over the propagation of local magnetic excitation via magnetostatic interaction in a linear array of nanomagnets is important for the spin logic devices [19, 20] and the so-called magnonic crystals [21], the microwave analogue of the photonic or phononic band gap crystals. The dynamic properties including the eigenfrequency spectra in coupled magnetic nanodiscs have been theoretically and experimentally demonstrated [22, 23]. However, the central question regarding the manipulation of magnetostatic interaction between the elements and their dynamic behaviour in an ordered array of magnetic vortices remains largely unexplored. In this paper, we have shown, by micromagnetic simulations, that the magnetostatic interaction between elements in an array can be actively controlled by introducing asymmetry via shape engineering and by manipulating the combination of vortex polarization and chirality in neighbouring elements. Particularly, we have studied the propagation of gyration of the magnetic vortex core along a linear array of nanomagnets under the application of a local time-dependent rotating magnetic field [24, 25]. We demonstrate an optimization of the transmittance and the propagation velocity of the locally excited vortex core gyration along the array. The inter-element magnetostatic interaction in the optimized structures may further be increased by the reduction in the separation between the elements below 25 nm, as used in this paper. However, fabrication of such structures using the existing lithographic techniques would be extremely challenging. On the other hand, the effect of shape asymmetry holds significantly in optimizing the propagation behaviour for an inter-element separation up to about 50 nm but the effect is more prominent for 25 nm and below. Hence, we have chosen a fixed value of the inter-element separation of 25 nm and tried to optimize the propagation behaviour by controlling the shapes of the elements.

2. Method

We have performed micromagnetic simulations to solve the Landau–Lifshitz–Gilbert equation using the object oriented micromagnetic framework (OOMMF), from the NIST website [26]. We have calculated the static magnetic configurations and the time evolution of magnetization in linear arrays of magnetic nanodiscs of various physical geometry produced under different magnetic history. The different magnetic history and the geometry of the constituent elements in the arrays result in magnetic ground states with six unique magnetic configurations named S1–S6, as shown in figure 1(a). Detailed description of micromagnetic simulation using OOMMF may be found elsewhere [27, 28]. The arrays are formed of six Ni81Fe19 (permalloy) elements of 40 nm thickness with circular shape or circles with one or two flat ends. The circular elements are of 200 nm diameter, while the flat-ended circles are formed by removing 15% of their diameters at one or two ends of the discs. The dimensions of the flat-ended discs in the x–y plane are 170 nm × 200 nm for one flat end and 140 nm × 200 nm for two flat ends. The edge to edge separation between the discs is fixed at 25 nm for all samples. Calculations were performed by dividing the samples into a two-dimensional array of cells with dimensions 5 × 5 × 40 nm3. All the discs have rough edges due to discretization with cuboidal cells and hence the referred element shapes correspond to the overall profiles of the discs. The cell size was found to provide a good compromise between the spatial resolution and the computational time. The linear dimensions of the cells are comparable to the exchange length, which is defined as $\sqrt{(A/2\pi M_s^2)}$ where $A$ is the exchange constant and $M_s$ is the saturation magnetization.
respectively, and has a value of about 5.8 nm in Permalloy. Further simulations of the ground states of the above arrays with $5 \times 5 \times 5 \text{nm}^3$ cells show that the overall nature of the ground states remains the same as those obtained by using the $5 \times 5 \times 40 \text{nm}^3$ cells, but there is a small amount of spatial variation of the magnetization along the thickness. This may introduce small changes in the magnetic volume charges in the individual discs. However, this is not expected to change the magnetostatic interactions between the discs mediated by magnetic surface charges, which is the key ingredient for the propagation of excitation as discussed in detail later in this paper. More detailed discussions regarding the dependence of micromagnetic simulation results on cell size may be found elsewhere [28, 29]. The finite thickness of the film affects the results through the demagnetizing field.

2.1. Method of preparation of tailored magnetic ground states in linear nanomagnet arrays

The geometry and strength of the applied static magnetic field ($H_a$) for obtaining tailored magnetic ground state configurations of the arrays are presented in figure 1(a). After applying $H_a$ along the $x$-direction for 12 ns, the field is reduced to zero and the magnetization is allowed to relax for 16 ns to reach the equilibrium. The damping constant $\alpha$ is set at 0.5 so that the precession dies down quickly and the magnetization fully relaxes within the simulation time. The simulations assume typical material parameters for Permalloy: $M_s = 860 \text{emu cm}^{-3}$, $A = 1.3 \times 10^{-6} \text{erg cm}^{-1}$, $H_k = 0$ and $g = 2.2$. S1 and S2 consist of circular discs arranged in an identical manner. The ground state of S1 is prepared by first saturating the magnetization with a 2 kOe field along the $x$-direction and then reducing the field to zero. The ground state of S2 is prepared by first applying a 4 kOe out-of-plane field and then by reducing the field to zero. In S1 and S2, the chirality of the vortex is not under control since in a circle the in-plane shape anisotropy is isotropic, and CW and CCW states are degenerate. However, in S3 and S4 we have attempted to control the chirality of the discs by introducing geometric asymmetry, i.e. by using flat-ended discs [30]. For S3, flat-ended discs were arranged in the same order. We first applied a 10 kOe field parallel to the $x$-direction and then reduced the field to zero. S4 was prepared by arranging the flat-ended discs in reverse order and by preparing the magnetic ground state under identical magnetic history to that for S3. S5 was prepared with discs with two flat ends with the motivation of facilitating the increase in the total magnetic side charges responsible for the energy transfer between the discs. In order to investigate the stability of the optimized structure (S4) to defects, S6 was designed by introducing triangular notched defects on the flat ends of alternative discs in S4.

2.2. Simulation of the time-resolved magnetization dynamics

First, the time-resolved dynamics of single isolated elements that constitute the linear arrays have been simulated by applying an in-plane pulsed field and the resonance frequencies were extracted from the corresponding fast Fourier transform (FFT) spectra. The gyration mode frequency is 1.26 GHz for the circular disc, and 1.39 GHz and 1.37 GHz for the circular discs with one flat end and two flat ends, respectively. The slight variations in the gyration mode frequency in the discs with flat ends stem from the variation of the potential energy in which the vortex core gyrate. The first disc of all types of arrays is then excited by the application of an in-plane ($x$-$y$ plane) magnetic field with 40 mT amplitude and rotating at the resonance frequency of that element in a geometry as shown in figure 1(b). The dynamic magnetization averaged over the entire sample volume and images of the same were saved for a total duration of up to 16 ns at intervals of 10 ps. A unique damping parameter $\alpha = 0.008$ for Permalloy [31] was assumed in the dynamic simulations. The dynamics of every individual element in the arrays were then extracted by analysing the series of time-resolved images.

3. Results and discussion

3.1. Magnetic ground states

Figure 1(a) shows the magnetic ground states at remanence ($H_a = 0$) for all types of linear nanodisc arrays. The polarization $p = 1$ (up) and $-1$ (down) are represented by black and white colours, respectively, and chirality $C = +1$ and $-1$ correspond to CW and CCW flux closure directions. Any changes in chirality between the consecutive discs are marked by the downward arrows. In S1, there is an antiferromagnetic ordering between the vortex cores while the chirality changes from disc 1 to disc 2 (CW to CCW) and again from disc 5 to disc 6 (CCW to CW). In S2, the cores have identical polarization ($p = -1$) for all discs but the chirality changes (CW to CCW) from disc 3 to disc 4. The ground state of S3 corresponds to identical core polarization ($p = +1$) for all discs and same (CCW) chirality from disc 1 to disc 5. However, the chirality switches to CW in disc 6. For S4, core polarization ($p = +1$) and chirality (CCW) for all discs are identical. In S5, discs 3 and 4 take a quasi-single domain ($S$-state) due to the strong magnetostatic interactions between the discs in the linear array although the other discs take a vortex state in the remanence. The magnetic ground state of S6 has a change in the core polarization in disc 2 ($p = +1$) and chirality in disc 6 (CCW to CW), when prepared under identical magnetic history to that for S4.

3.2. Time-resolved magnetization dynamics

Figures 2(a)–(f) show the time-resolved magnetization and the corresponding FFT spectra from individual discs in each array when only disc 1 was excited by a time-dependent rotating field. The time-domain data for all discs in the arrays have faster oscillations inside a slowly varying envelope, as shown by the dotted lines, similar to a wave packet. Here, we consider the first peak of the envelope, as marked by an arrow, as the reference and investigate how it propagates from disc 1 to disc 6 through the intermediate discs. The height of this peak in disc 1 is referred to as the master signal ($A_1$) while the same in disc 6 is referred to as the final transmitted signal ($A_6$). The transmittance is defined as $100 \times (A_6/A_1)$. The propagation velocity is defined as the velocity with which the master signal propagates from disc 1 to disc 6.
Figure 2. Time-resolved magnetization curves and the corresponding FFT spectra for linear arrays of nanomagnets: (a) S1, (b) S2, (c) S3, (d) S4, (e) S5 and (f) S6. The dotted lines show the envelope of the propagating wave packets in discs 1 and 6. The downward arrows represent the first peak of the envelope in discs 1 and 6 where the amplitude of the master signal ($A_1$) and the transmitted signal ($A_6$) are calculated.

3.3. Variation in master signal

A comparison of the time-dependent magnetization of all arrays reveals that the master signal of the gyrotropic oscillation in the first disc is different under the application of an identical magnetic field. The master signal is minimum in S1 (150.9 emu cm$^{-3}$) and increases steeply up to S4 (510 emu cm$^{-3}$) and then goes down slightly in S5 (390 emu cm$^{-3}$) and S6 (423 emu cm$^{-3}$). While the increase in master signal in arrays with the same element shape (S1 to S2 or S3 to S4) may be attributed to the variation in the inter-disc interaction, the large jump observed in arrays with different element shapes, such as from S2 to S3, may be attributed to the variation in the self-magnetostatic energy within the elements. Consequently, the vortex core finds itself in different potentials, which determines its oscillation amplitude ($A$) and frequency ($f$).

3.4. Variation in transmittance

A comparison of the percentage transmittance from disc 1 to disc 6, through the intermediate discs for all types of arrays except S5, is plotted in figure 3. The transmittance values to disc 6 are about 16% for S1, 19% for S2, 22% for S3, 37% for S4 and 36% for S6. The complicated profile of the time-dependent magnetization in S5 makes it difficult to estimate the disc to disc transmittance but the transmittance from disc 1 to disc 6 is about 26%. For all types of arrays except S1, the transmittance to disc 2 is efficient (>50%), while in S1 it is only about 15%. Beyond disc 2 the transmittance is nearly constant in S1. In S2 and S3 there is a sharp drop in transmittance at disc 3 and beyond that it varies slowly and becomes nearly constant from disc 5. In S2 and S6 the transmittance varies almost linearly with disc number except for a sharp increase at disc 3 in S6, which is not well
motion according to Thiele’s equation of motion \( \text{(32)} \).

Upon application of the magnetic field, the vortex core experiences a restoring force from the demagnetizing field and thus the gyration is maintained. During the gyration the complete flux closure structure breaks into partially flux closure arrangements and magnetic side charges are developed from the partially ferromagnetically ordered spin structures within the discs \([18]\). Two examples of these partial flux closure magnetic configurations and the origin of magnetic side charges are shown in figure 4. The resulting stray field disturbs the equilibrium of the neighbouring disc(s) and introduces gyration of the core and subsequently generates magnetic side charges in these discs. The inter-disc magnetostatic interaction between the side charges of the moving vortex, when displaced from the equilibrium, depending on whether the interaction energy is close to or far away from the equilibrium. Consequently, the gyration of the cores propagates from disc to disc.

3.5. Variation in propagation velocity

Interestingly, the increase in transmittance and the transmitted signal is associated with the increase in the propagation velocity of the peak excitation from disc 1 to disc 6. The calculated propagation velocities are 204.3 m s\(^{-1}\) for S1, 160.6 m s\(^{-1}\) for S2, 327.2 m s\(^{-1}\) for S3, 386.4 m s\(^{-1}\) for S4 and 290 m s\(^{-1}\) for S6. For the reason mentioned above we did not attempt to estimate the propagation velocity in S5.

3.6. Mechanism of the propagation of local excitation

Upon application of the magnetic field, the vortex core in disc 1 of each array undergoes a gyrotrropic rotational motion according to Thiele’s equation of motion \([32]\). The moving vortex, when displaced from the equilibrium, experiences a restoring force from the demagnetizing field and thus the gyration is maintained. During the gyration the complete flux closure structure breaks into partially flux closure arrangements and magnetic side charges are developed from the partially ferromagnetically ordered spin structures within the discs \([18]\). Two examples of these partial flux closure magnetic configurations and the origin of magnetic side charges are shown in figure 4(a). The resulting stray field disturbs the equilibrium of the neighbouring disc(s) and introduces gyration of the core and subsequently generates magnetic side charges in these discs. The inter-disc magnetostatic interaction between the side charges of the neighbouring discs continues to increase or decrease depending on whether the interaction energy is close to or far away from the equilibrium. Consequently, the gyration of the cores propagates from disc to disc.

3.7. Role of magnetostatic coupling and magnetic side charges

The observed variation in transmittance and the amplitude of the master signal may be described in terms of the magnetostatic coupling between the discs mediated by the magnetic charges \(\sigma = \vec{m} \cdot \vec{n}\) at the side surfaces of the discs. The contribution of magnetic volume charges \((- \nabla \cdot \vec{m})\) in a...
vortex structure is important for the dynamics of the individual discs. However, surface charges play the key role in the inter-disc interactions in an array. This was confirmed by varying the inter-disc separation above 25 nm (not shown), when the disc to disc transmittance becomes very weak due to the rapid decrease in the interaction between the surface charges. The combination of vortex core polarization and chirality plays important roles in determining the magnetic side charges. The magnetostatic energy is quantified as the surface integral of the product of the surface charges divided by the distance. If the inter-disc magnetostatic energy is negative, the system is close to the equilibrium and a further transfer of energy between the discs is not favourable. However, if the interaction energy is positive, the system is far from the equilibrium and the inter-disc transfer of energy is favourable. Using this simple principle, we interpret below the transmittance characteristics of various types of arrays and their dependence on three factors, the sign and magnitude of the surface charges and the distance between them.

Due to the local field excitation, the vortex core gyration in various discs in the arrays start at different times, and hence they are not in phase. This determines the dynamic magnetic side charge distribution, which is shown schematically in figure 4(b) for a particular instant of time. In S1, the magnetic side charges in discs 2–6 are very small, giving rise to a very small interaction energy between discs 1 and 2, and also the subsequent discs, and consequently the transmission is very poor from disc 1 to disc 2 until disc 6. In S2 and S3, the opposite side charges between discs 2 and 3 cause a small interaction energy between these discs and hence transmissions fall sharply. This causes very small amplitude of vortex core gyration and hence small magnetic side charges in the consequent discs and the overall transmission is low. However, in S4, a different scenario is observed. From disc 1 to disc 6 the magnetic side charges in consecutive discs are of the same sign resulting in a positive interaction energy between neighbouring discs, whose magnitude decreases systematically from disc 1 to disc 6 due to the decrease in the amount of surface charges. This gives rise to a high transmission and a linear decrease in transmission from disc 1 to disc 6 in S4. In S5, the appearance of S-states in discs 3 and 4 modifies the energy transfer mechanism from vortex core gyration to precession of spin in these discs. After about 3.3 ns the large energy transfer to disc 3 eventually switches it to magnetic vortex states but disc 4 retains the S-state. The overall energy transfer increases beyond that time but does not reach its maximum even after 16 ns. This system has a very slow response time and would not be very useful for applications. The sharp change in transmittance at disc 3 in S6 is not well understood. However, beyond disc 3 the transfer mechanism is similar to S4. In general, a number of frequency peaks or broad peaks are observed in the FFT spectra from all arrays despite the fact that the vortex structures have a single core in all cases. This is probably due to the non-linearity in the magnetic potential in which the vortex cores gyrate due to the large amplitude of the rotating field, the anisotropy of the shape of the discs and the inter-disc interactions. This is most prominent in S6, presumably due to the large anisotropy in the shape of the discs.

On the other hand, the appearance of side charges in disc 2 in all types of arrays produces stray field in disc 1 and amplifies the gyration amplitude in disc 1. The energy is related only to the surface charges $\sigma$ appearing along the envelope of the disc. Due to the largest surface charge and area of interaction between discs 1 and 2, the interaction is the strongest in S4 and the peak amplitude of gyration (master signal) in disc 1 is maximal for S4. It decreases systematically on both sides of S4 for the above-mentioned reason.

4. Conclusion

In conclusion, we have performed micromagnetic simulations to investigate and control the propagation of locally excited vortex dynamics in linear arrays of magnetic nanodiscs. The individual disc takes the vortex state in remanence. We focus upon the optimization of transmittance, propagation velocity and transmitted amplitude of the local excitation by controlling the magnetic ground states of the arrays including the core polarization and chirality of the vortices. The optimization of the above parameters is based upon the control over the inter-disc magnetostatic interaction mediated by magnetic side charges generated by the gyration of the vortices. Various combinations of core polarization and chirality are obtained by varying the magnetic history while obtaining the ground states and by engineering the shapes of the discs and their arrangement in the array. This study can be easily extended to two- and three-dimensional arrays of magnetic vortex systems to create and tailor artificial band structures of magnetic excitation modes, which may lead to the formation of magmonic crystals with higher energy efficiency. The large changes in transmittance and propagation velocity obtained in different types of nanomagnet arrays may be used to construct magnetic logic devices and nanoscale delay lines.

Acknowledgment

SB acknowledges the financial assistance (grant no SR/FTP/PS-71/2007) by the Department of Science and Technology, Government of India. The authors also gratefully acknowledge the financial assistance of a Grant-in-Aid for Scientific Research in Priority Area ‘Creation and control of spin current’ (19048013) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References
