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## FAST TRACK COMMUNICATION

# Gyration mode splitting in magnetostatically coupled magnetic vortices in an array

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## Abstract

We present the experimental observation of gyration mode splitting by the time-resolved magneto-optical Kerr effect in an array consisting of magnetostatically coupled Ni<sub>81</sub>Fe<sub>19</sub> discs of 1  $\mu\text{m}$  diameter, 50 nm thickness and inter-disc separations varying between 150 and 270 nm. A splitting of the vortex core gyration mode is observed when the inter-disc separation is 200 nm or less and the splitting is controllable by a bias magnetic field. The observed mode splitting is interpreted by micromagnetic simulations as the normal modes of the vortex cores analogous to the coupled classical oscillators. The splitting depends upon the strength of the inter-disc magnetostatic coupling mediated by magnetic side charges, which depends strongly on the magnetic ground states of the samples.

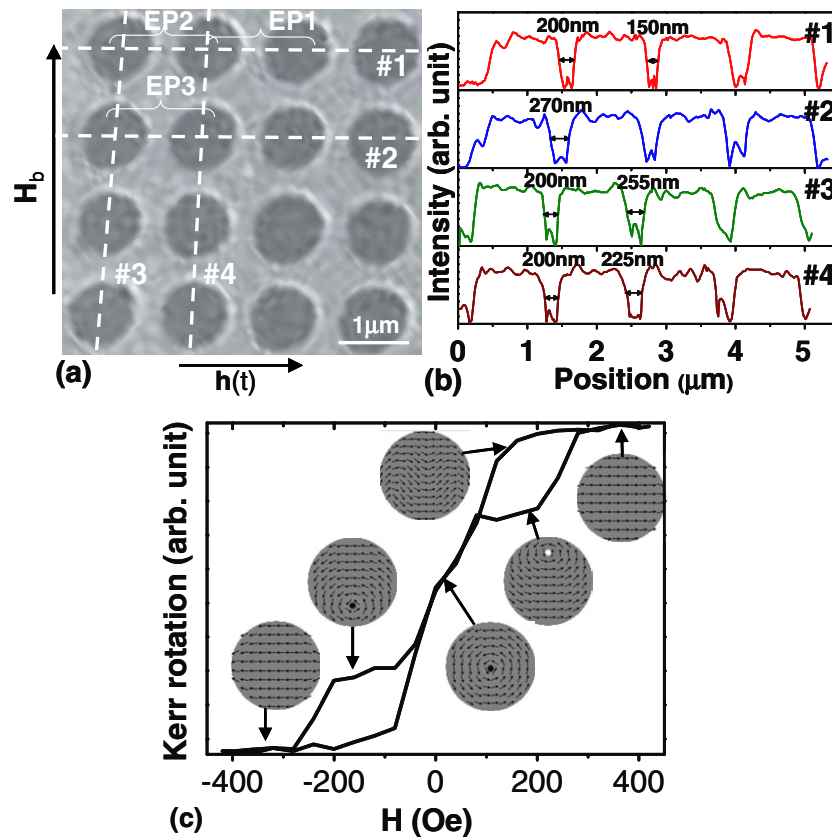
(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Ordered nanomagnet arrays are important from fundamental and applications viewpoints, including patterned magnetic media [1], magnetic random access memory [2], logic devices [3] and spin torque induced magnetization processes [4, 5]. In confined magnetic elements competition between exchange, dipolar and anisotropic magnetic energies yields various domain structures [6] and for thin micrometre and sub-micrometre magnetic discs a magnetic vortex state with curling in-plane spin configuration and out-of plane core is energetically favoured [7]. The core radius is about 10 nm and its polarization  $p$  can be either up ( $p = +1$ ) or down ( $p = -1$ ) and the sense of the in-plane flux closure configuration (chirality  $c$ ) can be clockwise ( $c = +1$ ) or counterclockwise ( $c = -1$ ). The magnetic vortex is a non-localized magnetic

soliton [8] and according to Thiele's equation [9], the moving vortex experiences an in-plane gyrotropic force perpendicular to its velocity. When the core is displaced from its equilibrium position, the restoring force from the demagnetizing field and the gyrotropic force result in a spiral motion of the vortex core [10, 11] with a frequency in the sub-gigahertz range. In addition, low-order magnetostatic spin waves have been observed by time-resolved magneto-optical Kerr effect (MOKE) microscopy [12–14] and Brillouin light scattering [15, 16]. Switching of the vortex core polarization has been shown by applying a large static magnetic field [17, 18] or by coherent excitation with low-amplitude magnetic field pulses [19, 20].

The experiment reveals that the lowest order azimuthal spin-wave mode splits into a doublet due to the coupling between spin waves and vortex core gyration [21].



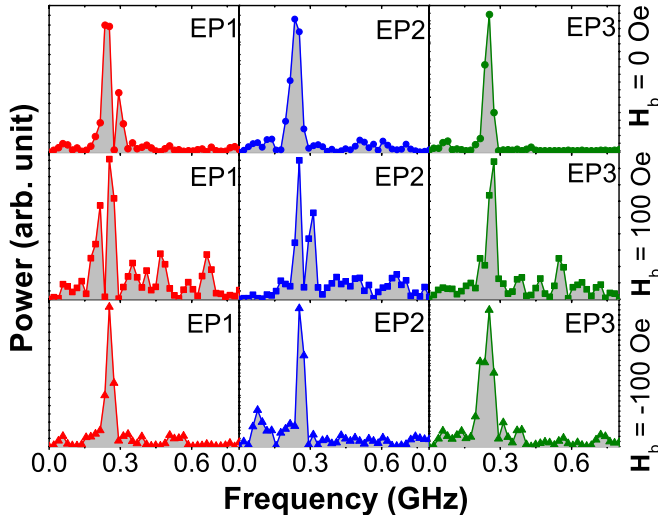
**Figure 1.** (a) Scanning electron micrograph of an array of Permalloy nanodiscs deposited on a Au microstrip line is shown with the directions of the external bias and pulsed magnetic fields. The white dotted lines indicate the regions over which the cross-sections are taken, as shown in (b). (c) A typical hysteresis loop from disc 1 in the array measured by micro-MOKE is shown. The magnetization reversal mechanism is indicated by simulated magnetic images of a single Permalloy disc showing the saturated magnetized states, and nucleation, propagation and annihilation of magnetic vortices.

Theoretically, the coupled frequencies of vortex pairs were calculated and symmetry classification of the vortex modes was made for layered magnetic nanodots [22]. Further, the dispersion and density of states of the collective dynamics of magnetostatically coupled vortices in an ordered array have been calculated [23], and the localization of modes was suggested to be controlled by engineering the array and by introducing defects and impurities [24]. Present efforts on magnonic crystals [25] are based mainly upon the quasi-single domain magnetic structures. However, magnetic vortex-based structures are expected to be magnetically more stable due to their flux closure configurations and have the potential to form a new class of magnonic crystals, but very little has been done to this end. A recent experiment [26] of the dynamics of magnetic vortex pairs confined in a single Permalloy element of ellipsoidal shape has revealed a number of modes due to the in-phase and out-of-phase motions of cores with two different polarizations. However, experiments of collective dynamics in magnetostatically coupled vortices in an array are lacking in the literature. Here, we present the experimental time-resolved magnetization dynamics of pairs of magnetostatically coupled  $\text{Ni}_{81}\text{Fe}_{19}$  (Permalloy) discs in an ordered array. We have observed a splitting in the collective gyration mode in pairs of discs with an inter-disc (edge to edge) separation of 200 nm or below, which varies with the bias magnetic field. We have modelled the experimental results by time-dependent

micromagnetic simulations and interpreted the results due to the variation of magnetic ground states of the pairs of discs in the array.

## 2. Experimental details

An array of Permalloy discs with  $5 \times 50$  elements with nominal dimensions of diameter 1 μm, thickness 50 nm and inter-disc separation varying between 140 nm and 270 nm was fabricated at the centre of a Au microstrip line deposited on a Si substrate by electron-beam lithography and electron-beam evaporation. Figure 1(a) shows the scanning electron micrograph of the region at the left-top corner of the array, the dynamics of which has been described in this paper. Figure 1(b) shows the cross-sections of the sample along the dotted lines as shown in figure 1(a). Figure 1(c) shows the magnetic hysteresis loop measured by micro-MOKE from disc 1, i.e. the element at the extreme top-left corner of the array. The MOKE data show typical vortex-like behaviour [27]. At low field values the vortex state is observed and with the increase in the external field the competition between various magnetic energies breaks the symmetry of the vortex and the core shifts from the centre. This process generates magnetized regions parallel to the applied field, which enhances with the external field until the vortex annihilates at the annihilation

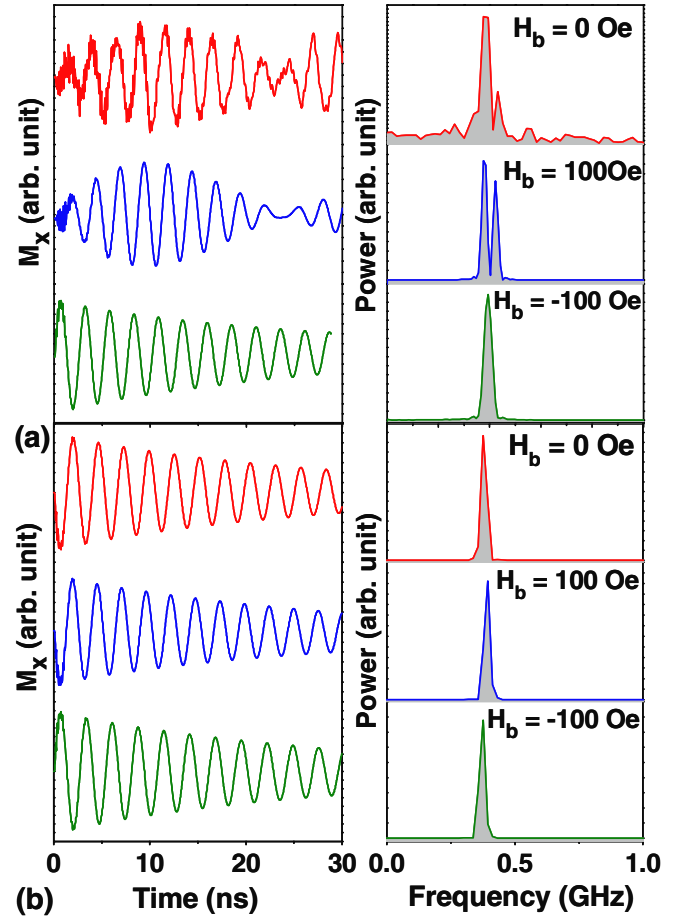


**Figure 2.** The FFT spectra of the time-resolved Kerr rotations are shown for Permalloy disc pairs EP1, EP2 and EP3 at bias fields  $H_b = 0$  Oe,  $H_b = 100$  Oe and  $H_b = -100$  Oe.

field and a uniformly magnetized state appears. The reduction in external field first causes a quasi-uniform magnetization until the vortex nucleates at the nucleation field. Further reduction in the field causes a similar process as described above and the whole process is depicted in figure 1(c) with typical simulated magnetization states of a single Permalloy disc at various external field values. The experimentally observed nucleation and annihilation fields are about 120 Oe and 280 Oe, respectively. The time-resolved MOKE apparatus has been described in detail elsewhere [28]. The dynamics is excited by a pulsed magnetic field of 60 ps rise time, 115 ps fall time and 60 Oe peak amplitude, produced by sending a pulsed current from a pulse generator to the Au microstrip line. The induced magnetization dynamics was probed by measuring the MOKE signal, with an elliptical shaped laser spot of 408 nm wavelength and 40 ps pulse width, positioned carefully on the disc pairs, as a function of the delay time between the optical and electronic pulses. The pulse generator was gated at 10 kHz frequency and the Kerr rotation was measured in a phase sensitive manner with a lock-in amplifier. An in-plane variable bias magnetic field ( $H_b$ ) is applied to the sample. The directions of  $H_b$  and the pulsed field  $h(t)$  are shown in figure 1(a).

### 3. Results and discussion

Time-resolved magnetization dynamics was measured from three different disc pairs in the array, named as EP1, EP2 and EP3 in figure 1(a), to investigate the effect of inter-element magnetostatic interaction and the consequent static magnetic configurations of the discs. The inter-disc separations for EP1, EP2 and EP3 are 150 nm, 200 nm and 270 nm, respectively. Figure 2 shows the fast Fourier transform (FFT) spectra of the time-resolved Kerr rotations at different bias fields from these samples. At  $H_b = 0$  Oe, the FFT spectra show a broad single resonance peak for EP2 and EP3 but a clear splitting of the resonance mode for EP1. The frequency splitting is greater

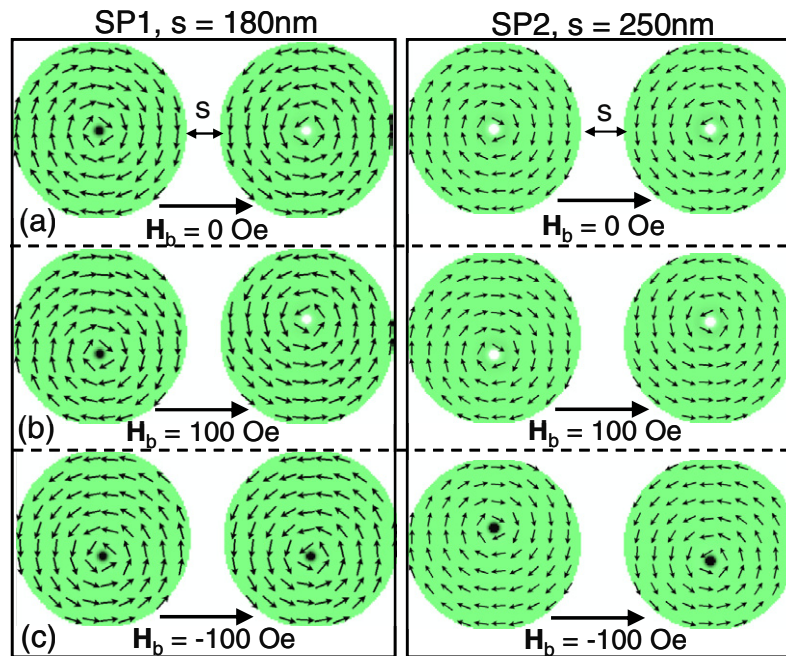


**Figure 3.** Simulated time-dependent magnetization and the corresponding FFT spectra of Permalloy disc pairs (a) SP1 and (b) SP2 at bias fields  $H_b = 0$  Oe,  $H_b = 100$  Oe and  $H_b = -100$  Oe are shown.

than 50 MHz, which is just above our experimental resolution ( $\sim 40$  MHz). At  $H_b = 100$  Oe, a clear splitting in the resonance modes for EP1 ( $>60$  MHz) and EP2 ( $>50$  MHz) is observed, while EP3 shows a broad resonance peak with a small shoulder, which may indicate an unresolved mode splitting. However, at  $H_b = -100$  Oe, a damped sinusoidal oscillation of Kerr rotation with time and a single resonance peak in the FFT spectra are observed, for all three disc pairs. The application of a positive bias field increases the frequency splitting for EP1 and creates splitting in EP2 but does not affect EP3. It also enhances the amplitude of the secondary mode by shifting the vortex cores away, as described later in this paper. On the other hand, the application of a negative bias field completely suppresses the mode splitting in EP1 and EP2, even though the magnetostatic coupling is sufficiently strong in these disc pairs. This indicates that the combination of vortex core and chirality and the inter-disc separation controls the dynamics, and the full micromagnetic configuration of the samples must be taken into account to understand the observations.

### 4. Micromagnetic simulation

Time-dependent micromagnetic simulations were performed by solving the Landau–Lifshitz–Gilbert (LLG) equation [29]



**Figure 4.** Simulated magnetic ground states of SP1 and SP2 at bias fields (a)  $H_b = 0$  Oe, (b)  $H_b = 100$  Oe and (c)  $H_b = -100$  Oe are shown. The colour map (white–green–black; white–grey–black in printed version) represents the out-of-plane component of magnetization. The core polarizations are represented as white  $p = +1$  and black  $p = -1$ .

using the Object Oriented Micromagnetic Framework (OOMMF) from the NIST website [30]. The key to the observed dynamics is the relative core polarization and orientation of the vortices in the measured disc pairs. However, the disc pairs belong to a larger array and the effects of other elements of the array are important for the accurate determination of the frequency and damping of the dynamics [31]. The collective dynamics would depend on the dimensions of the individual elements, inter-disc separation, defects and surface quality of the discs, and accurate inclusion of all of the above parameters is not possible within our existing computational resources. Hence, we have considered only the measured pairs of discs in a simplified model, which can qualitatively describe the experimental observations. We have simulated the dynamics of two different pairs of Permalloy discs with dimensions as obtained from the experiment but with inter-disc separations of 180 nm (SP1) and 250 nm (SP2). Calculations were performed by dividing the samples into a two-dimensional array of cuboidal cells with dimensions  $5 \times 5 \times 50$  nm<sup>3</sup>. Further simulations with  $5 \times 5 \times 5$  nm<sup>3</sup> cells do not show any appreciable change in the magnetic ground states. The linear dimensions of the cells are less than the exchange length of Permalloy (5.8 nm). The static magnetic configurations were obtained by first saturating the sample along the bias field ( $H_b$ ) direction. The field was then reduced to  $H_b$  and the magnetization was allowed to relax for 20 ns. The damping coefficient  $\alpha$  was set at 0.9 to fully relax the magnetization within the simulation time. The simulations assume  $4\pi M_S = 10.8$  kOe,  $A = 1.3 \times 10^{-6}$  erg cm<sup>-1</sup>,  $H_K = 0$  and  $g = 2.2$  for Permalloy. A pulsed magnetic field with a rise time of 60 ps and a peak amplitude of 60 Oe was applied to the sample in the experimental configuration, and the collective dynamic magnetization averaged over the disc pairs

and images of the same were obtained for a total duration of up to 30 ns at intervals of 20 ps. The value of  $\alpha$  was set at 0.008 in the dynamic simulations. The images were later analysed to extract the dynamics of the constituent discs from the disc pairs.

Figures 3(a) and (b) show the simulated time-dependent magnetization and the corresponding FFT spectra for SP1 and SP2 at three different values of  $H_b$ . The simulations clearly reproduce the splitting of the gyration mode. No splitting is observed in SP2 at all values of  $H_b$  and also in SP1 at  $H_b = -100$  Oe. However, a clear splitting is observed in SP1 at  $H_b = 0$  Oe and 100 Oe. The experimentally observed frequencies are lower than the simulated frequencies and also from previously reported results [32] probably due to the slight loss in the magnetization and defects in the measured samples. We focus on the mechanism responsible for the gyration mode splitting. Figures 4(a)–(c) show the magnetic ground states of SP1 and SP2 at three values of  $H_b$ . For SP1 and at  $H_b = 0$  Oe the vortex cores in the two discs have opposite polarization ( $p_1 p_2 = -1$ ) and chirality ( $c_1 c_2 = -1$ ) and are located at the centre of the discs. At  $H_b = 100$  Oe, the core polarization and chirality remain unaffected but the cores shift away from the centre in the opposite direction and in the direction perpendicular to  $H_b$  (south–north). However, when  $H_b = -100$  Oe,  $p_1 p_2 = +1$  and  $c_1 c_2 = +1$ , the cores shift in the south–south configuration. For SP2 the lack of magnetostatic coupling between the cores is evident from the occurrence of the same core polarization ( $p_1 p_2 = +1$ ) at all values of  $H_b$ , but  $c_1 c_2 = -1$ . For  $H_b = 0$  Oe the cores are located at the centre of the discs but at  $H_b = 100$  Oe the cores shift from the centre in the south–north configuration and for  $H_b = -100$  Oe the cores take the north–south configuration.

The sense of rotation of the vortex core depends only on its polarization and is independent of the chirality [24].

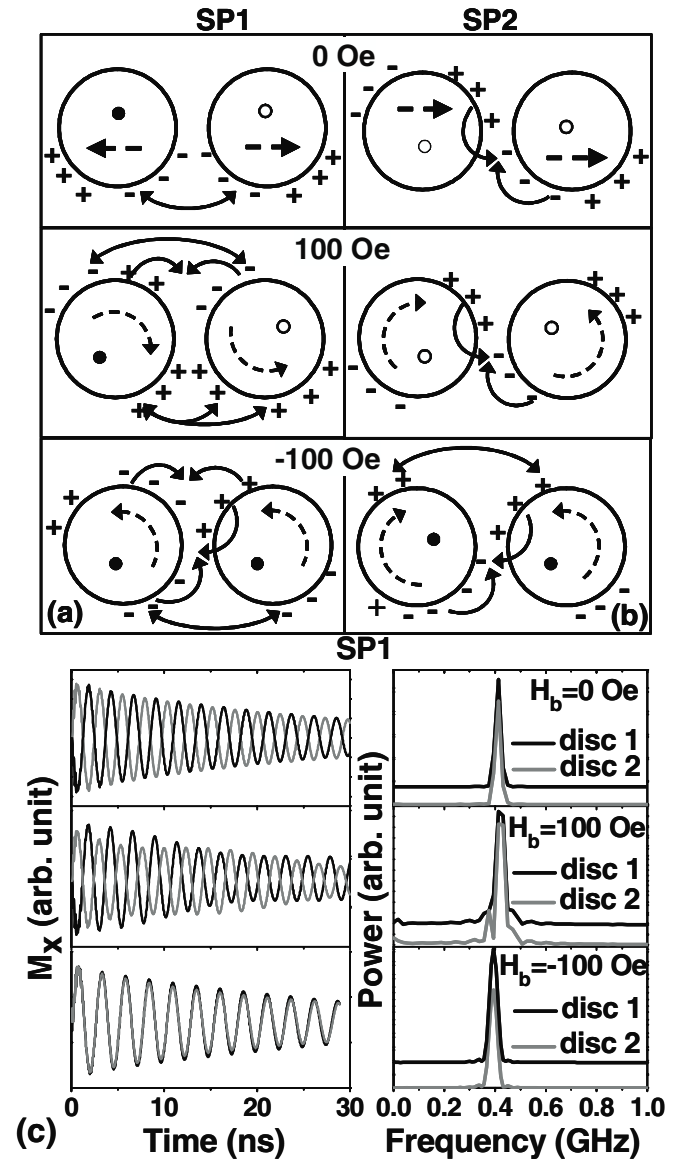
Consequently, the application of the pulsed field modifies the relative orientation of the cores further, as they gyrate. For SP1 at  $H_b = 0$  Oe, the cores gyrate in the opposite sense and the magnetic side charges of the same sign develop on the surfaces facing each other resulting in a large positive magnetostatic interaction and energy transfer between the discs. The south–north configuration of the cores for SP1 at  $H_b = 100$  Oe and their opposite sense of gyration cause a large positive interaction energy between the magnetic side charges as shown in figure 5(a)<sup>4</sup>. For  $H_b = -100$  Oe, the discs have the same core polarization, while they are in the south–south configuration and the application of the pulsed field causes them to oscillate in phase with each other. The resulting magnetic side charges have a negative interaction energy and no or little energy transfer between the discs. In SP2 (figure 5(b)), the cores are of the same polarization and undergo the same sense of gyration due to the pulsed field. The interaction energy between the magnetic side charges on the nearest surfaces of the discs is always negative and the energy transfer between the discs is negligible.

In order to gain more insight we have extracted the dynamics of the constituent discs in the pairs as they undergo the collective dynamics. Figure 5(c) shows the time-dependent magnetization and the corresponding FFT spectra of the SP1 disc pair at three different bias fields. At  $H_b = 0$  Oe, the discs oscillate in the opposite direction with identical frequencies but for  $H_b = 100$  Oe, even the constituent discs show two peaks. For  $H_b = -100$  Oe the cores oscillate in phase with identical frequencies. As a result, for  $H_b = 0$  Oe and 100 Oe, the collective dynamics of the discs shows the normal modes of oscillations similar to coupled classical oscillators. For  $H_b = 100$  Oe, there is a large inter-disc magnetostatic interaction. The combination of large  $H_b$  and the large magnetostatic interaction between the discs may introduce some non-linearity in the magnetic potential energy. It has been shown experimentally and theoretically that the solution of Thiele's equation with higher order terms in the potential energy results in additional modes in the gyration of the vortex core in a single magnetic disc [33, 34]. When pairs of these discs undergo a collective gyration, these modes are possibly amplified in the normal modes of oscillation. Due to weak magnetostatic coupling between the discs in SP1 at  $H_b = -100$  Oe and at all bias fields in SP2, the normal mode frequencies are nearly identical and we observe only a single gyration frequency in the collective dynamics.

## 5. Conclusions

Using the time-resolved MOKE experiment and micromagnetic simulations, we have investigated the dynamics of pairs of magnetostatically coupled Permalloy discs in an array. The strength and sign of the magnetostatic fields are distinctly different for various inter-disc separations and bias fields. The appearance of different combinations of core polarization, chirality and relative positions of the cores is observed in the magnetic ground states, and the application of pulsed field

<sup>4</sup> See EPAPS document for the time-resolved images of the simulated disk pairs.



**Figure 5.** A schematic of the dynamic process is shown for (a) SP1 and (b) SP2 at different bias fields. The dotted arrows correspond to the parallel in-plane spins created due to the shift of the vortex core from the centre of the discs, and the solid arrows represent the positive and negative contributions to the magnetostatic interaction energy between the discs. (c) Simulated time-resolved magnetization and corresponding FFT spectra of the individual discs in SP1 at three different bias fields are shown.

induces different dynamics depending on the ground states. When the inter-disc separation is above 200 nm there is no magnetostatic coupling between the vortex cores in the two discs and they have the same polarization. However, for an inter-disc separation of 200 nm or below, the vortex cores are magnetostatically coupled, which can be further manipulated by a bias magnetic field. When  $H_b$  is set at zero or 100 Oe, the core polarizations and the chiralities are of opposite signs, which results in a large interaction energy due to magnetic side charges of the same sign on the facing surfaces. Subsequently, the normal modes of oscillation in the disc pair show a clear frequency splitting. For  $H_b = 100$  Oe, the magnetostatic interaction energy and the energy due to the external

field cause a non-linearity in the potential well for the vortex core and the gyration of the constituent discs shows a weak frequency splitting, which gets further amplified in the normal modes of oscillation. However, for  $H_b = -100$  Oe, the cores have the same polarization similar to the disc pairs with weak magnetostatic coupling. The interaction energy is very small due to the side charges of opposite sign, and the normal mode frequencies are nearly identical, showing practically no frequency splitting. The influence of the inter-disc separation and the bias field on the magnetic ground states and subsequently on the mode splitting in the dynamics opens up the possibility of controlling a band of collective gyration modes in a large vortex lattice, leading towards the applications in a new class of magnonic crystals.

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