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Spin Wave Excitations and Winter's Magnons in Vertically Coupled Vortex State Permalloy Dots

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Abstract Circular soft magnetic dots are the main elements of many proposed novel spintronics devices, capable of fascinating spin-based electronics applications, from extremely sensitive magnetic field sensors, to current-tunable microwave vortex oscillators. Here, we investigate static and broadband dynamic magnetization responses of vertically coupled Permalloy (Py) magnetic dots in the vortex state in layered nanopillars (experiment and simulations), which were explored as a function of in-plane magnetic field and interlayer separation. Under reduction of magnetic field from saturation for the field range just above vortex-vortex ground state. We observe a metastable double vortex state for each of the dots. In this state, novel kinds of spin waves (Winter's magnons along domain walls between vortex cores and half-edge antivortex) are excited. For dipolarly coupled circular Py(25 nm)/Cu(20 nm)/Py(25 nm) trilayer nanopilars of diameter 600 nm, a small in-plane field splits the eigenfrequencies of azimuthal spin wave modes inducing an abrupt transition between acoustic (in-phase) and optic (out-of-phase) kinds of the low-lying coupled spin wave modes. Qualitatively similar changes (although more gradual and at higher values of in-plane fields) occur in the exchange coupled Py(25 nm)/Cu(1 nm)/Py(25 nm) trilayer nanopillars. These findings are in qualitative agreement with micromagnetic dynamic simulations.

Keywords Magnetic vortex · Spin waves · Dipolar · Exchange coupling

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Layered magnetic nanopillars have become the main "building blocks" in spintronics. The bulk of the current knowledge on magnetization dynamics in the vortex state, however, is related to the single vortex, or laterally coupled vortex state dots. Recent static investigations revealed stabilization of the vortex state in ferromagnetic layers of the dipolarly coupled ferromagnetic layer/nonmagnetic spacer (metal, insulator)/ferromagnetic layer (F/N/F) nanopillars [1]. Influence of the character of coupling (dipolar vs. exchange) on the excited spin wave modes in F/N/F nanopillars remain, however, unclear. Moreover, the major part of the previous studies of the vertically coupled vortex state dots has been done in asymmetric conditions by using the dots made of different magnetic materials (typically Co and Py). Using symmetric (the same thickness and material) circular ferromagnetic layers would give a unique opportunity to investigate the influence of the character of interlayer coupling (i.e., interlayer exchange vs. dipolar coupling) on the spin wave dynamics in pure vortex-vortex coupled systems without influence of additional factors such as magnetic anisotropy.

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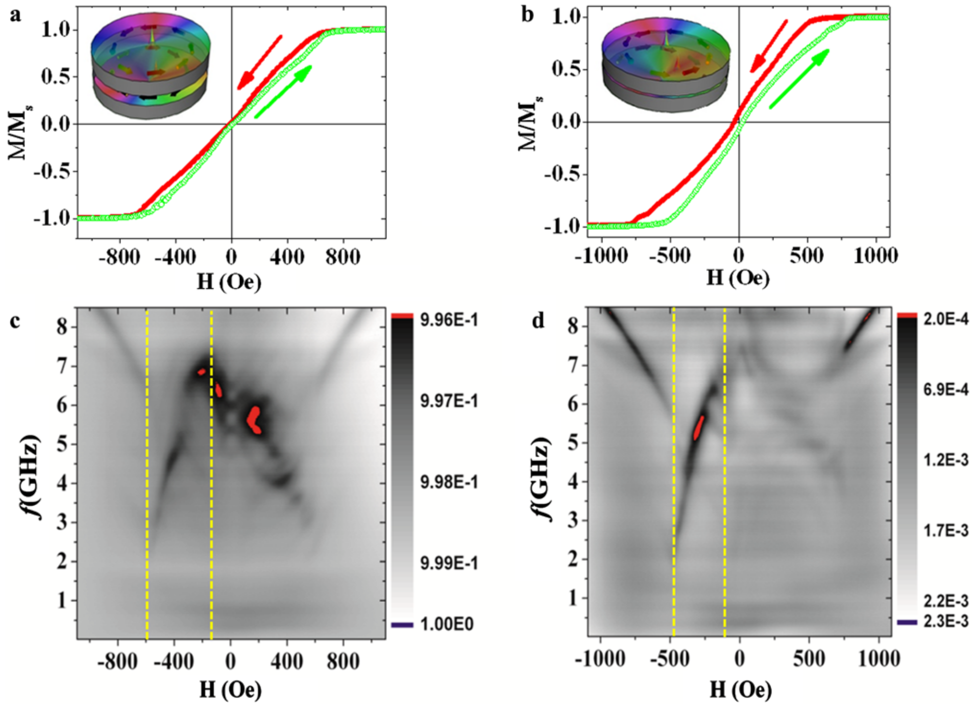

Fig. 1 Magnetization hysteresis and excitation frequencies of the dipolarly coupled nanopillars Py/Cu(20 nm)/Py, (**a**), (**c**) and the exchange coupled nanopillars Py/Cu(0.9 nm)/Py, (**a**), (**d**)

Here, we investigate, experimentally and by simulations and analytical estimations, the static and dynamic response of the vertically coupled Py dots with two spacer thicknesses, of 0.9 and 20 nm, in Py/Cu/Py nanopillars to external magnetic fields. We study the variation of both static and dynamic response between saturated and magnetic vortex states applying a bias in-plane field and compare the results with the spin wave spectra of uncoupled dots published previously [2].

Two set of patterned samples in the form of square arrays of trilayer Py(25 nm)/Cu(d)/Py(25 nm) circular dots were fabricated by a combination of lithography and lift-off techniques on Si(100) substrate. The samples have Py layer thicknesses of $L = 25$ nm, diameter $D = 600$ nm, and a large square lattice period with the interdot center-to-center distance of 1000 nm to minimize the dipolar lateral coupling. The thickness of the Cu spacer for the first type of samples is $d = 0.9$ nm (further IEC—interlayer exchange coupled-trilayer), while for the second type is $d = 20$ nm (DIC—dipolar interlayer coupled-trilayer). The interlayer coupling and the material parameters have been estimated by broadband ferromagnetic resonance response of the continuous (i.e., without lithography) reference Py films.

We perform a room temperature study of the spin wave spectra by broadband vector network analyzer based VNA-FMR technique [2]. The set-up allows applying a rf field $\mathbf{h}$ at different angles with respect to the in-plane bias field $\mathbf{H}$. As it is necessary to have excitation torque $\mathbf{h} \times \mathbf{M}_0 \neq 0$ ($\mathbf{M}_0$ is the static magnetization), the parallel pumping scheme will be used ($\mathbf{h}_{\mathrm{rf}\parallel}\mathbf{H}$) because such driving field excites only the spin eigenmodes localized near the vortex in the areas, where there is an effective torque and the uniform FMR-mode is suppressed. The data were analyzed on the basis of transmission model [2]. The estimated magnitude of in-plane rf field is below 0.14 Oe that assures the linear response, so we can exclude any effects of nonlinear inter-mode interaction.

The DC magnetization curves for both the IEC and DIC trilayer nanopillars (measured at 300 K, see Fig. 1a,b) show a vortex like hysteresis and are in qualitative agreement with the hysteresis loops for simulated coupled circular dots in F/N/F nanopillars with centered vortices present in both the F-layers at remanence [3]. To characterize the vortex state in j-layer, we denote the vortex core polarizations as p_j and chiralities C_j ($j = 1, 2$). The loops simulated with OOMMF [4] (not shown), made by reducing the field to zero from initial saturation of the dots magnetization, indicate a centered double vortex remanent state and are qualitatively similar to the measured ones. As we shall see below, however, magnetization dynamics of DIC nanopillars points out the existence of a statistical distribution of the antiparallel (APC, $C_1C_2 = -1$) and parallel chiralities (PC, $C_1C_2 = +1$) of the vortex states in DIC dots. Magnetization reversal (Fig. 1a,b) reveals that the vortex annihilation H_a fields are larger for IEC than for DIC nanopillars. This indicates that the dipolar coupling, present in both IEC and DIC pillars, is strengthened by antiferromagnetic exchange in the IEC dots with an ultrathin Cu spacer.

Two types of broadband measurements have been carried out in order to detect high frequency spin wave modes. In

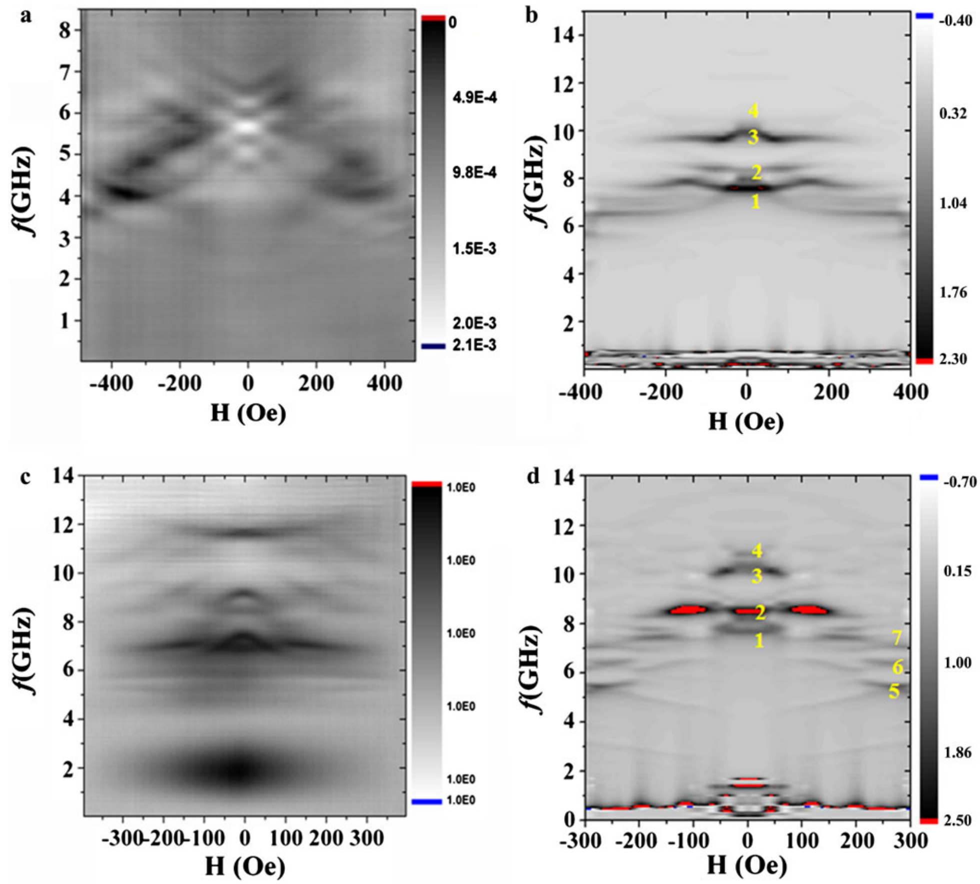

Fig. 2 Measured absorption frequency spectra as a function of applied in-plane field without vortex annihilation for the DIC (**a**) and IEC (**c**) Py/Cu/Py nanopillars. Simulated eigenfrequencies with for the DIC (**b**) and IEC (**d**) nanopillars. Marked modes are explained in the text

the first type of experiment, we initially saturated the magnetization and made a frequency sweep at the fixed in-plane bias field, starting from a negative bias field, and ending with a positive field, that forces a saturated state. Below the saturated state, we detect the Kittel-like quasiuniform spin eigenmode. At lower field, the trilayer dots pass through a metastable double vortex configuration in each of the coupled dots. This region (marked by the dotted yellow lines in Fig. 1c,d) appears before entering into the vortex–vortex state. This state is characterized by the excitation of relatively low (few GHz) frequency spin waves, highly dependent on the field, that have a similar field dependence for both DIC and IEC samples with frequencies shifted to high values in the case of the IEC sample. Those excitation spin modes are known as "Winter's magnons" or flexural oscillations of the domain walls connecting the vortex and antivortex cores and have been recently observed for single Py dots [2]. Further reduction of the magnetic field close to zero reveals the emergence of the vortex–vortex modes. We focus further on the high frequency modes only. The high frequency spin waves reveal dramatic (more clear visible for DIC dots) changes of their spectra in relatively small fields (Fig. 1c,d). Two frequency doublets observed in the small field region, abruptly transform into multiple satellites when increasing the bias field above some critical value of about 40 Oe (more abrupt in the case of DIC trilayers than for IEC ones).

In order to investigate in more detail, the low field changes in broadband frequency response of the coupled layers; we carried out a second type of the experiments by measuring the averaged broadband response using multiple scans within minor loops (i.e., without annihilating any of the two vortices in the ferromagnetic layers; see Fig. 2a,c). Both DIC and IEC dots reveal now more clearly strong changes of the spin wave response at low fields (symmetric response with respect to the zero field confirms the existence of centered vortices in both Py layers). To identify the observed frequency peaks, we employ standard schematics describing the spin waves (SW) excited in nearly centered vortex state according to number of the nodes in dynamic magnetization along the azimuthal m and radial n directions. For a single uncoupled dot SW with $n = 0$, we have undegenerated eigenfrequencies for $m = \pm 1$ due to the dynamic vortex-SW interaction [5] resulting in formation of the doublets with the frequency splitting of 1.3 GHz ($L = 25$ nm, $R = 300$ nm).

The interlayer coupling energy in the F/N/F stack consists of two parts: exchange (essential only if $d < 2$ nm) and magnetostatic coupling (for all d). The volume density of the exchange energy can be written as $w_{\mathrm{int}}^{\mathrm{ex}} =$

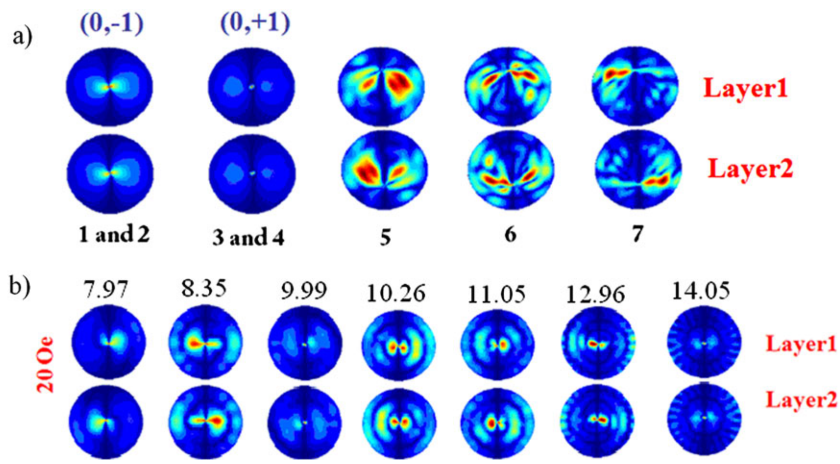

Fig. 3 (**a**) Simulated spatial distributions of the vortex dynamic magnetization at different bias fields for the DIC dots with AP chirality ($\Delta M_x/M_s$ is presented). The numbers label eigenfrequencies in Fig. 2. (**b**) Simulated distributions of the amplitude profiles for the eigenmodes at 20 Oe. On top of each mode, the frequency (in GHz) is specified. In both the cases, the dynamic magnetization distributions in the top and bottom Py layers are shown

$-(J/LM_S^2)\boldsymbol{\mu}_1 \cdot \boldsymbol{\mu}_2$ (J is the interlayer exchange integral and $\boldsymbol{\mu}_j$ are the layer magnetizations). The magnetostatic coupling energy density in the main approximation can be written via the F-layer dipole moments $w_{\text{int}}^{\text{dip}} = (V/(d+L)^3)\langle\boldsymbol{\mu}_1\rangle\langle\boldsymbol{\mu}_2\rangle$ placed in the centers of the dots of volume V. We see that the corresponding interaction fields H_{int}^{ex} and H_{int}^{dip} can be added to each other because they follow the same angular dependence $\sim\cos(\Theta)$, where Θ is the angle between the averaged layer dynamic magnetizations. Since for Cu the maximum value of $J \sim 0.14$ erg/cm^2, estimation shows that the magnetostatic coupling dominates for both the Cu-spacer thicknesses $d = 0.9$ and 20 nm explored. The dipolar interaction energy is $w_{\text{int}}^{\text{dip}} \propto \langle\boldsymbol{\mu}_1\rangle \cdot \langle\boldsymbol{\mu}_2\rangle \propto -C_1C_2m_1m_2$, where $m_1, m_2 = \pm 1$ are the indices of the azimuthal SW forming the doublets in the 1st and 2nd layers. Each of the $(0, m_j)$—frequencies splits into the frequencies of in-phase and out-of-phase modes. The in-phase (out-of-phase) mode frequency is lower for ferromagnetic (antiferromagnetic) interlayer coupling.

Dynamic micromagnetic simulations using the code OOMMF [4] are carried out (applying 5 Oe Gaussian field pulse of the length of 1 ps) to clarify the origin of spin wave spectra changes at small applied fields (Fig. 2c,d). We note that zero field experiments reveal the existence of a pair of doublets in the frequency range where the lowest split azimuthal mode doublet is expected. The presence of the second doublet is attributed to the presence of a statistic distribution of APC and PC configurations of the vortex chiralities in each of the DIC dots forming the trilayer nanopillars, and this is fully reproduced by the simulations (Fig. 2b,d). Indeed, the finite field simulations for DIC dots show an abrupt additional splitting in the SW azimuthal modes at applied magnetic fields exceeding 15 Oe. The assumption about a 50 % mixture (statistics is checked by the simulations, relaxing the dots from a random distribution of magnetization) of the APC and PC nanopillars describes qualitatively well the experimental observations with four weakly field dependent spin wave modes at small fields that are transformed to multiple and strongly field dependent SW frequencies above some critical magnetic field. Figure 2c,d compares experiments and simulations for low field response in IEC dots with a mixture of 70 % APC and 30 % PC chiralities. Similar, but more gradual (than for DIC dots) changes are seen in the SW eigenmodes.

External fields above 15 Oe abruptly induce qualitative changes both in the frequencies and, especially, in the relative phase of the SW modes excited in the coupled Py layers. Figure 3a shows simulated spatial distributions of the vortex dynamic magnetization in the DIC dots with APC chirality (presented by the reduced x-component, $\Delta M_x/M_s$), which reveals strong changes above 15 Oe. Being of the acoustic type (i.e., the two Py-layers response is nearly in-phase; see the modes 1, 2, 3, 4) at the ground state ($H = 0$), the $\Delta M_x/M_s$ displacements change to have an optic character between the coupled dots when a small external magnetic field above 15 Oe is applied (see Fig. 3b, where bias field of 20 Oe is applied). This occurs because at the fields different from zero, each vortex is pushed toward a different edge of the dot, and differences of phase appear as a result of the changes in the symmetry around the dot center that were present in the dots at zero field. In the APC configuration at zero field, the main two modes occur at 8.13 GHz (counterclockwise (CCW) motion) and at 10.15 GHz (clockwise (CW) motion) (see the modes 1 and 4 in Fig. 3a). At higher fields, the first mode splits into other two modes, at 7.97 (CCW) and 8.35 (CCW) GHz at 20 Oe (Fig. 3b). The second mode also splits into other two modes with the frequencies of 9.99 (CW) and 10.26 GHz (CW) at 20 Oe. At higher fields (30 Oe), the previous mode at 7.97 GHz splits again into two modes having the frequencies of 7.41 (CCW) and 7.8 GHz (CCW). All of these modes are field dependent. At higher fields, new modes appear (Fig. 2b,d).

To summarize, magnetization dynamics of vertically coupled vortex state layers in Py/Cu/Py circular trilayer nanopillars applying in-plane magnetic field reveal substantial differences with respect to a single layer response. Zero field splitting of the azimuthal spin wave modes shows a frequency shift due to the coupling influenced by the relative chiralities of the Py layers. If the external in plane magnetic field exceeds a critical value, it leads to the excitation of multiple modes, which are characterized not only by their strong field dependence, but also by their differences in relative phase of the dynamic response of the ferromagnetic layers.

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