

# Spin wave quantization and dynamic coupling in micron-size circular magnetic dots

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We report on the observation of spin wave quantization in square arrays of micron size circular magnetic  $\text{Ni}_{80}\text{Fe}_{20}$  dots by means of Brillouin light scattering spectroscopy. For a large wavevector interval several discrete, dispersionless modes with a frequency splitting of up to 2.5 GHz were observed. The modes are identified as magnetostatic surface spin waves laterally quantized due to in-plane confinement in each single dot. The frequencies of the lowest observed modes decrease with increasing distance between the dots, thus indicating an essential dynamic magnetic dipole interaction between the dots with small interdot distances.

Regular arrays of magnetic islands, like dots and wires, are currently attracting increasing scientific interest due to their potential applications in magnetic sensors and in high-speed, high-density, nonvolatile magnetic random access memory devices [1,2]. Progress made during the last decade in lithographic techniques and the analysis of matter enables the fabrication of well-controlled, laterally defined magnetic islands down to submicrometer sizes. However, increasing the memory density by scaling the bit sizes down to submicrometers is not trivial, since the small size and high lateral density of the islands in arrays affect their magnetic properties dramatically due to increasing demagnetizing fields and magnetic dipole interaction between the islands. Although static properties of patterned magnetic structures have been studied earlier to a certain extent [3-5], the investigation of their dynamic properties, which are of great importance for high-speed optimization of possible devices, is just beginning [6-9]. In this Letter we report an experimental study of spin wave properties of tangentially magnetized circular micron-size magnetic dots, arranged in a

square array. Arrays with different dot thicknesses, dot diameters, as well as dot separations have been investigated. The quantization of the modes caused by the in-plane spin wave confinement in a single dot is observed for the first time. The obtained results also demonstrate an essential dynamic inter-dot coupling in arrays with distances between the dots of 0.1  $\mu\text{m}$ .

The samples were made of permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) films with thicknesses  $d$  of 10, 20 and 40 nm deposited in UHV onto a Si (111) substrate by means of e-beam evaporation. The films were covered by Pd overlayers to prevent oxidation. Static magneto-optic Kerr-effect (MOKE) measurements on the non-patterned films demonstrated a high quality of the films documented by a very low ( $< 5$  Oe) induced in-plane magnetic anisotropy. After being tested, the films were patterned to create two-dimensional square arrays of circular dots. Patterning was performed by x-ray lithography using a negative resist with a lift-off process with Al coating and ion milling. Different samples with various combinations of dot diameters ( $D = 1$  and  $2 \mu\text{m}$ ), dot thicknesses ( $d = 10, 20, 40$  nm) and dot separations ( $\delta = 0.1, 0.2, 1$  and  $2 \mu\text{m}$ ) were prepared. Scanning electron micrographs demonstrating four patterning layouts are shown in Figure 1. The overall dimensions of the arrays were  $500 \times 500 \mu\text{m}^2$ .

The spin wave properties in the Damon-Eshbach spin wave mode geometry [10] (the transferred in-plane wavevector is perpendicular to the applied field) were investigated by means of Brillouin light scattering spectroscopy using a computer controlled tandem Fabry-Perot interferometer which is described elsewhere [11,12]. Light of a single-mode  $\text{Ar}^+$  laser operating at a wavelength of  $\lambda_{\text{laser}} = 514.5$  nm was focused onto the sample and the frequency spectrum of the backscattered light was analyzed. The value of the transferred wavevector  $q_{\parallel}$  was varied by changing the angle of light incidence  $\theta$  measured against the surface normal of the sample:  $q_{\parallel} = (4\pi/\lambda_{\text{laser}}) \cdot \sin\theta$ . The collection angle of the scattered light was chosen small enough to ensure a reasonable resolution in  $q_{\parallel}$  of  $\pm 0.8 \times 10^4 \text{cm}^{-1}$ . At small angles of light incidence the directly reflected beam was blocked by small blinds inserted into the collection aperture.

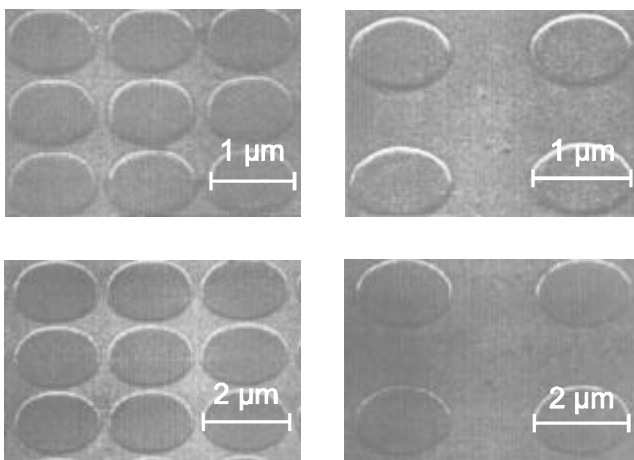


Fig. 1: SEM micrograph of the investigated dot arrays. In the upper part two samples with a dot diameter of  $1 \mu\text{m}$  and a dot separation of  $0.1 \mu\text{m}$  (left) and of  $1 \mu\text{m}$  (right), and at the bottom two samples with a dot diameter of  $2 \mu\text{m}$  and a dot separation of  $0.2 \mu\text{m}$  (left) and  $2 \mu\text{m}$  (right) are shown. Due to the oblique incidence of the electron beam the circular dots appear ellipsoidal.

Figure 2 shows the anti-Stokes side of a typical Brillouin light scattering spectrum for a transferred wavevector of  $q_{\parallel} = 0.21 \cdot 10^5 \text{ cm}^{-1}$  for the sample with a dot thickness of 40 nm, a dot diameter of 2  $\mu\text{m}$ , and a dot separation of 0.2  $\mu\text{m}$ . An external field of 600 Oe was applied in-plane along the array axis. Near 7.0, 7.9, 9.8, 11.4 and 14 GHz several distinct spin wave modes are clearly observed. All these modes are magnetic excitations as concluded from the measured field dependence of the mode frequencies. The peak near 14 GHz is also observed on the non-patterned films. It has a dot thickness dependence  $\omega \propto d^2$ , and it shows no essential Stokes/anti-Stokes asymmetry. Therefore, it is identified as corresponding to the perpendicular standing exchange dominated spin wave mode. The value of the exchange stiffness, calculated from the measured frequencies of these modes is  $A = 1 \cdot 10^{-6} \text{ erg/cm}$ , which is in a good agreement with the results of other studies [13].

By changing the angle of light incidence the value of  $q_{\parallel}$  is varied and the dispersion of the observed mode is obtained as demonstrated in Fig. 3 for the array of dots with 2  $\mu\text{m}$  dot diameter and 0.2  $\mu\text{m}$  dot separation. As it is seen in the figure, several discrete dispersionless modes are detected over the measured wavevector interval. A tendency that the splitting between neighboring modes decreases with increasing mode frequencies is clearly seen. A similar effect has already been observed for magnetic wires [7]. It is due to the fact that the group velocity  $V_g = \partial\omega/\partial q$  of the Damon Eshbach mode decreases with increasing wavevector. In the case of wires, where the spin wave modes are characterized by quantized equidistant wavenumbers [14]  $q_{\parallel,i}$ , this fact necessarily leads to a decreasing frequency splitting. Two-dimensional quantization conditions in a circular dot are not so simple, as are those for the wires [7]. Therefore, it is not surprising that the splitting between the three lowest lying modes, shown in Fig. 3 presents an exception from this rule. Using a numerical procedure [15], the frequencies of the Damon Eshbach mode and the first perpendicular standing spin wave mode for a continuous film of same thickness ( $d = 40 \text{ nm}$ ) were calculated, using the values of the demagnetizing factors, obtained from separate static magneto-optic Kerr magnetometry. The results of the

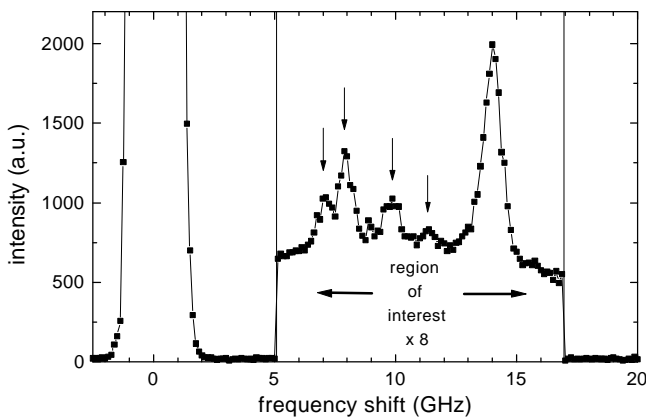


Fig. 2: Obtained BLS spectrum for a sample with a dot diameter of 2  $\mu\text{m}$  and a dot separation of 0.2  $\mu\text{m}$  for  $q_{\parallel} = 0.21 \cdot 10^5 \text{ cm}^{-1}$  with an external field of 600 Oe applied in-plane demonstrating the existence of several discrete spin wave modes. The peaks corresponding to laterally quantized modes are indicated by arrows. In the “region of interest” the scanning speed was reduced by a factor of eight, increasing the number of photon counts by this factor. At zero frequency shift the peak of the elastically scattered light appears.

calculation are plotted in Fig. 3 as full lines. The frequency of the uniform mode of a single disc ( $\omega = 7.35 \text{ GHz}$ ) calculated using the Kittel formula [16], is shown as a horizontal dashed line as well. The calculations clearly demonstrate that for large transferred wavevectors ( $2\pi/q_{\parallel} \ll D$ ) the measured dispersion converges to the dispersion of a continuous film of the same thickness, and the two quantized lowest modes have frequencies near the frequency of the uniform mode.

The five lowest spin wave modes of arrays of dots with the same dot thickness as presented in Fig. 3, but with a smaller dot diameter ( $D = 1 \mu\text{m}$ ) are shown in Fig. 4 for two different dot spacings. First, it is clear from a comparison of Figs. 3 and 4, that the wavevector interval, where each mode is observed, scales approximately as  $D^{-1}$ . This result is in agreement with the theoretical analysis performed in [7], which has shown that the light scattering intensity from a given spin wave mode confined in an island is determined by the Fourier transform of the mode profile over the island. Second, changing the thickness of the dots, one observes that the frequency splitting between neighboring modes decreases with decreasing dot thickness, in accordance with the fact that the group velocity of the Damon-Eshbach mode at a given  $q_{\parallel}$  decreases with decreasing film thickness.

The above presented experimental findings lead us to the conclusion that the observed dispersionless, resonance-like modes are the Damon-Eshbach spin waves, quantized due to lateral confinement in a single dot. Earlier studies of the magnetostatic modes of *tangentially* magnetized macroscopic discs using a ferromagnetic resonance technique [17] do not present any comparison of the experimental findings with the theory. Surprisingly, despite numerous publications on inhomogeneous magnetostatic modes in finite-size magnetic samples (see, e.g., [18] and references therein) there is no appropriate theoretical description of such modes up to now. This can be probably explained by the low symmetry of the problem. In fact, in his pioneering work, Walker [19] considered an axially magnetized spheroid. Due to axial symmetry, the analytic solution of the Walker equation is possible in this case and it can be expressed in terms of Legendre functions. The direction of the in-plane magnetization of the tangentially magnetized dot breaks the axial symmetry of the Walker

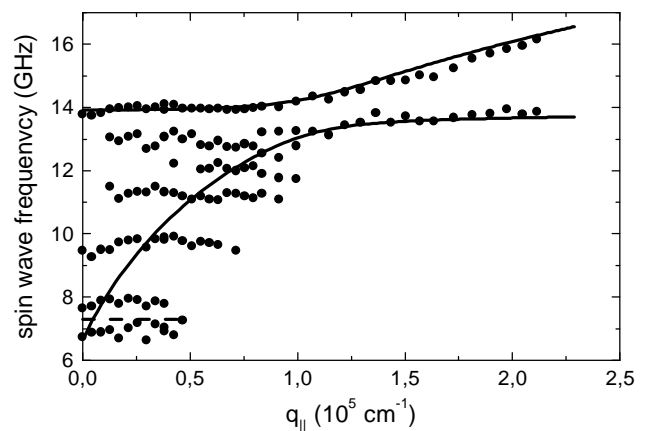


Fig. 3: Obtained spin wave dispersion curve for a square array of dots with a dot thickness of 40nm, a dot diameter of 2  $\mu\text{m}$  and a dot separation of 0.2  $\mu\text{m}$ . An external field of 600 Oe was applied in-plane along the axis of the array lattice. The solid lines show the results of a spin wave calculation for a continuous film of the same thickness as the dots. The dashed line marks the calculated frequency of the uniform mode of a single dot.

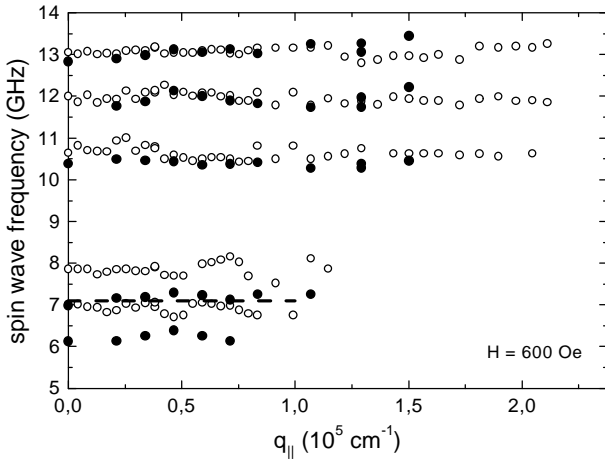


Fig. 4: Dispersion of the five lowest spin wave modes measured on a square array of dots with a dot thickness of 40nm, a dot diameter of 1  $\mu\text{m}$ . Open symbols indicate data for a dot separation of 0.1  $\mu\text{m}$ , full symbols of 1  $\mu\text{m}$ . The dashed horizontal line indicates the calculated frequency of the uniform mode of a single dot.

equation, and, correspondingly, that of possible mode profiles [20]. The solution (analytical or numerical) of the Walker equation, corresponding to a tangentially magnetized disc is still needed. However, a qualitative analysis of the mode frequencies in a tangentially magnetized dot shows that there are non-uniform modes with frequencies both higher and lower than the frequency of the uniform mode, as follows. For large wavevectors, when the lateral confinement is not important, the modes converge to spin waves in an infinite film (see above). Here there exist two types of spin wave modes: the Damon-Eshbach modes ( $\vec{q}_{||} \perp \vec{M}$ ) with a positive group velocity and the backward volume modes ( $\vec{q}_{||} \parallel \vec{M}$ ) with a negative group velocity. Therefore, there can exist modes in a dot with their frequencies below and above the frequency of the uniform mode depending on their main in-plane direction, along which the corresponding wavenumber is largest. Since our scattering geometry is sensitive to the modes with this direction perpendicular to the static magnetization, only the modes with higher frequencies are observed. Since the considered spin waves are the magnetostatic modes and magnetic dipole interaction is long-range, the question of possible interdot mode coupling is of importance. Also, from the practical point of view, interdot coupling restricts the density of dot arrays in, e.g., magnetic memory applications. Figure 4 shows the frequencies of the spin wave modes, obtained on arrays having the same dot thicknesses and dot diameter, but with different interdot distances: open symbols correspond to  $\delta = 0.1 \mu\text{m}$ , whereas full symbols correspond to  $\delta = 1 \mu\text{m}$ . A clear frequency upshift of the two lowest modes of the sample with  $\delta = 0.1 \mu\text{m}$  documents the existing interdot mode coupling. The weaker influence of the interdot coupling on higher modes can be understood as follows: Higher modes have mode

profiles with a high number of nodes. The dynamic dipole field created by such profiles outside the dot is weaker compare to that of the homogeneous mode. Therefore the dynamic interdot mode coupling caused by those fields is weaker.

In summary we have observed spin wave quantization in tangentially magnetized circular magnetic dots, arranged in a square array. The quantized modes are studied for samples with different dot diameters and thicknesses, as well as with different interdot distances. The observed modes are identified as surface magnetostatic (Damon-Eshbach) spin waves laterally quantized due to confinement in a single dot. The presence of interdot mode coupling is found. For a full description of the frequencies and the mode profiles of the dots further theoretical work is required.

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