Quantized spin wave modes in micron size magnetic discs

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We report on the observation of spin wave quantization in tangentially magnetized $Ni_{80}Fe_{20}$ discs by means of Brillouin light scattering spectroscopy. For a large wave vector interval several discrete, dispersionless modes with a frequency splitting up to 2.5 GHz were observed. The modes are identified as being magnetostatic surface spin wave modes quantized by their lateral confinement in the disc. For the lowest modes dynamic magnetic dipolar coupling between the discs is found for a disc spacing of 0.1μm.

Patterned magnetic films are attracting increasing interest due to their possible applications in magnetic sensors and in high-speed, high-density nonvolatile magnetic random access memory [1, 2]. Progress made in the last decade in lithographic techniques made it possible to produce well-controlled, laterally defined magnetic islands. However, by reducing the dimensions of the magnetic structures, the magnetic properties change dramatically due to size dependent demagnetization fields, dynamic magnetic dipole interaction and confinement effects.

While static magnetic properties of micron size magnetic structures have been studied to a certain extend [3-5], the investigation of the dynamic properties, which are of great importance for the optimization of high-speed devices, is just beginning [6-9]. In this paper we report on the investigation of the dynamic magnetic properties of tangentially magnetized circular disc, arranged in a square array. For this purpose spin waves in various disc arrays with different disc diameters, disc separations as well as different disc thicknesses were investigated.

The samples were made of permalloy ($Ni_{80}Fe_{20}$) films due to the intrinsically low magnetic anisotropy of this material, grown by means of e-beam evaporation in an UHV-evaporation system onto chemically cleaned Si(111). The films were covered by Pd overlayers to prevent oxidation. Static magneto-optic Kerr-effect (MOKE) measurements performed on unpatterned areas of the films demonstrate their high quality, which is attested by a low in-plane anisotropy (< 5 Oe) and coercivity (< 2 Oe). After being tested the films were patterned to create square arrays of circular discs. Patterning was performed by x-ray lithography using a negative resist and a lift off process with Al coating and ion milling. Samples with different disc diameters (D = 1 and 2 μm), disc separations (d = 0.1, 0.2, 1 and 2 μm) and disc thicknesses (d = 10, 20 and 40 nm) were prepared. The overall dimensions of the arrays are 800×800 μm^2.

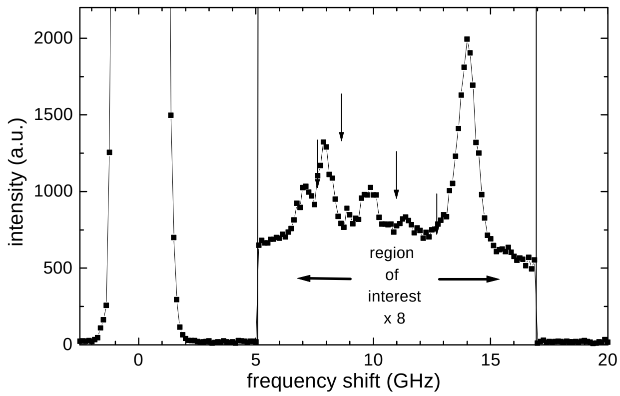

Fig. 1: Obtained BLS spectrum for a sample with a disc diameter of 2 μm and a disc separation of 0.2 μm for $q_{||} = 0.21\cdot10^5$ cm^{-1} with an external field of 600 Oe applied in-plane demonstrating the existence of several discrete spin wave modes. The peaks corresponding to laterally quantized 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.

The spin wave properties were tested by means of Brillouin light scattering spectroscopy in the Damon-Eshbach mode geometry (the wavevector transferred in the scattering process is perpendicular to the applied field, both lying in the film plane) using a computer controlled tandem Fabry Perot interferometer which is described elsewhere [10, 11]. Light of a single-moded Ar$^+$ laser operating at a wave length of λ = 514.5 nm was focused onto the sample and the backscattered light was frequency analyzed. The value of the transferred wave vector $q_{||}$ was varied by changing the angle of light incidence θ measured against the surface normal of the sample: $q_{||} = 4\pi/\lambda\cdot\sin\theta$.

Figure 1 shows the anti-Stokes side of a typical Brillouin light scattering spectrum for a transferred wave vector $q_{||}$ = $0.21\cdot10^5$ cm^{-1} for the sample with a thickness of D = 40 nm, a disc diameter of d = 2 μm and a disc separation of d = 0.2 μm. 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 seen in the spectrum. From the measured field dependence of these modes it can be concluded that all the modes observed in Fig. 1 are magnetic excitations. The spin wave mode near 14 GHz is identified as the perpendicular standing exchange dominated spin wave mode, because a) it shows the characteristic thickness dependence of the frequency $w \propto d^{-2}$, b) it appears in the continuous film as well.

By changing the angle of light incidence the value of $q_{||}$ was varied and the dispersion was measured as demonstrated in Fig. 2 for the sample with a disc thickness of 40 nm, a disc diameter of 2 μm and a disc separation of 0.2 μm. As it can be seen in Fig. 2 several discrete, dispersionless spin wave modes are detected over a continuous wavevector interval converging for large wave vectors to the dispersion curve of the respective continuous film. The splitting between the modes decreases with increasing mode number – an effect earlier observed in an array of magnetic wires [7]. In the case of wires the quantized spin wave modes are characterized by equidistant wavenumbers $q_{||,i} = (\pi/w)\cdot n$ with w the wire width and n the mode number, and for the eigenfunctions of the dynamic magnetization a cosine function was assumed [12]. In the present case of circular disks the quantization of $q_{||}$ and the corresponding eigenfunctions are not known (see below). The group velocity $v_g = \partial\omega/\partial q$ of the Damon-Eshbach mode decreases with increasing wave vector resulting in a decreasing frequency splitting between neighbored quantized modes with increasing mode number.

For reference, using a numerical procedure [13], the frequency of the Damon Eshbach mode and the first perpendicular standing spin wave for a continuous film of thickness d = 40 nm were calculated using the demagnetization factors obtained from separate static MOKE measurements. The results of the calculation are plotted in Fig. 2 as solid lines. The frequency of the uniform mode of a single disc (w = 7.35 GHz) is also shown in Fig. 2 as a horizontal dashed line. The calculation clearly demonstrates, that the obtained dispersion of the patterned sample converges for large wave vectors ($2\pi/q_{||} << D$) to the dispersion curve of a continuous film of the same thickness, and also that the frequencies of the two lowest modes lie near the frequency of the uniform mode of a single disc.

The influence of the disc separation on the frequencies of the spin wave modes is illustrated in Fig. 3 where the five lowest modes for the samples with a disc diameter of 1 µm and disc separations of 0.1 µm and 1 µm are shown. The sensitive dependence of the frequencies of the two lowest modes on the spacing indicates an essential dynamic magnetic dipole coupling between discs. The coupling is only observed for the lowest modes likely because these modes have a mode profile close to the uniform mode and thus having a stronger dipolar stray field than the higher modes with more nodal lines in the mode profile.

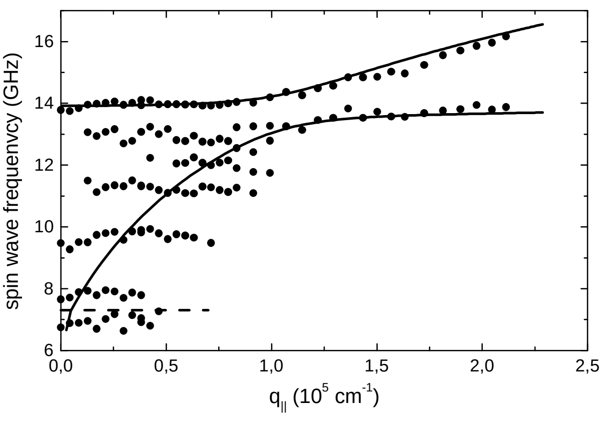

Fig. 2: Obtained spin wave dispersion curve for a square array of discs with a disc thickness of 40 nm, a disc diameter of 2 µm and a disc separation of 0.2 µm. An external field of 600 Oe was applied in-plane along one axis of the array lattice. The solid lines show the results of a spin wave calculation for a continuous film of the same thickness as the discs. The dashed line marks the calculated frequency of the uniform mode of a single disc.

Comparing Figs. 2 and 3 it is worth noting that the interval in which each mode is observed, scales with the disc diameter approximately as D^{-1}. This agrees with the results of the theoretical analysis performed for magnetic wires in [7], showing that the light scattering intensity from a given spin wave mode confined in a magnetic island is given by the Fourier transform of the mode profile over the island.

The above presented experimental results lead us to the conclusion that the observed dispersionless, resonance-like modes are dipolar spin waves quantized due to the lateral confinement in a single magnetic disc. The eigenfunctions of the quantized modes are not known likely because of the low symmetry of the in-plane magnetized discs. In his pioneering work Walker [14] considered an axially magnetized spheroid. Due to the axial symmetry, an analytic solution of the Walker equation exists. In our case the in-plane magnetization of the disc breaks the axial symmetry of the Walker equation. A qualitative analysis of the spin wave modes in a tangentially magnetized disc shows that there are modes with frequencies higher and lower than that of the uniform mode. This can be qualitatively understood as follows: Due to confinement and thus a quantization along both in-plane axes there exist both eigenmodes with the wavenumber [12] aligned parallel and perpendicular to the applied field. The former mode would correspond to a backward magnetostatic volume mode with its frequency shifted down with respect to the uniform mode due to the finite wavenumber [15], whereas the latter mode would correspond to the dipolar surface mode geometry with an upshift in frequency.

In summary we have observed spin wave quantization in an array of tangentially magnetized micron size discs. The quantized modes are studied in various samples with different disc diameters, thicknesses, as well as different disc separations. The modes observed are identified as being surface magnetostatic (Damon-Eshbach) spin waves quantized due to the lateral confinement in a single disc. The presence of an essential dynamic magnetic dipole coupling between neighboring discs is demonstrated for small disc separations. For a full description of the frequencies and the mode profiles further theoretical work is needed.

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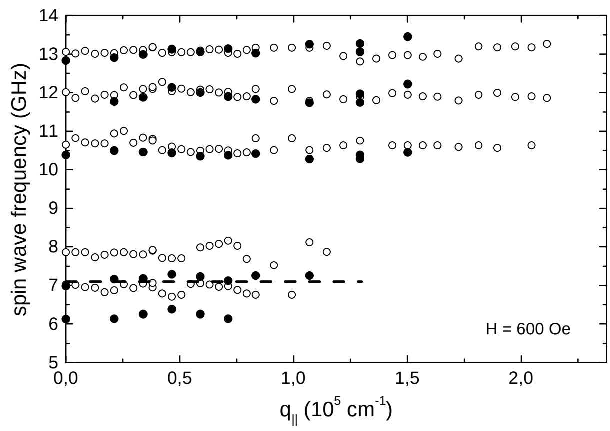

Fig. 3: Dispersion of the five lowest spin wave modes measured on a square array of discs with a disc thickness of 40 nm and a disc diameter of 1 µm. Open symbols indicate data for the disc separation d = 0.1 µm, full symbols d = 1 µm. The dashed horizontal line indicates the calculated frequency of the uniform mode of a single disc.

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