Lateral Quantization of Spin Waves in Micron Size Magnetic Wires

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We report on the observation of quantized surface spin waves in periodic arrays of magnetic $Ni_{81}Fe_{19}$ wires by means of Brillouin light scattering spectroscopy. At small transferred wave vectors ($q_{\|} \cong 0-1.0 \times 10^5$ cm^{-1}) several discrete, dispersionless modes with a frequency splitting of up to 0.9 GHz were observed for the wave vector oriented perpendicular to the wires. From the frequencies of the modes and the wave-vector interval where each mode is observed, the modes are identified as dipole-dominated surface spin-wave modes of the film with quantized wave-vector values due to a lateral standing wave condition. [S0031-9007(98)07540-1]

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Patterned magnetic films are attracting increasing interest due to their potential applications in magnetic storage devices and sensors. Although static properties and coupling phenomena in magnetic films patterned on the micron scale have been studied extensively [1–4], high-frequency dynamic properties of such films have been rarely investigated. On the other hand, the study of spin-wave properties in conventional finite size systems is well established, such as the investigation of so-called Walker modes in magnetic spheroids [5], and of dipolar-dominated surface modes (Damon-Eshbach modes) in finite-thickness slabs with infinite lateral dimensions [6]. For periodic, micron-sized magnetic structures, such a study has been still lacking, likely due to the high requirements both concerning the sample quality and the performance of the Brillouin light scattering experiment to detect the rather weak spin-wave signals.

In this Letter we report on the observation of quantization of spin waves in an array of magnetic wires. The quantization effects are identified as being due to the finite width of the wires. The evolution of the Damon-Eshbach mode of a continuous film from the discrete eigenmode spectrum of the wires with increasing wave vector, i.e., with diminishing influence of the finite size effect, is demonstrated and quantitatively described by a model based on quantized modes. We show that both the frequency values and the wave-vector intervals, where these modes are observed, are in good agreement with our proposed model.

The samples are made of a 200 Å thick permalloy ($Ni_{81}Fe_{19}$) film deposited in UHV onto a Si(111) substrate by means of e-beam evaporation. Patterning was performed using x-ray lithography. The patterning masks were fabricated by means of a JEOL 5D2U nanopattern generator at 50 keV. X-ray exposure was performed at the super-ACO facility (LURE, Orsay, France) using a negative resist with a liftoff process with Al coating and ion milling. Two samples with periodic arrays of wires with a wire width $w = 1.8$ μm and distances between the centers of the wires, of 2.5 and 4 μm (i.e., wire separations of 0.7 and 2.2 μm) were prepared. The length of the wires was 500 μm. The patterned area for each of the two investigated samples was 500×500 μm^2.

The spin-wave properties were investigated by using a computer controlled tandem Fabry-Perot interferometer as described elsewhere [7]. Laser light of a single-moded Ar^+ laser operating at a wavelength of $\lambda_{\text{laser}} =$ 514.5 nm with a power of 50 mW was focused onto the sample, and the frequency spectrum of the backscattered light was analyzed. An external field of 500 Oe was applied along the wires. The in-plane wave vector $q_{\|}$ transferred in the light scattering process was oriented perpendicular to the wires. Its value was varied by changing the angle of light incidence θ measured against the surface normal: $q_{\|} = (4\pi/\lambda_{\text{laser}})\sin\theta$. It is important to note that usually, due to the wave-vector (or momentum) conservation law, $q_{\|}$ is considered to be the wave vector of the spin waves taking part in the scattering process and thus tested in the experiment. In our case the connection between $q_{\|}$ and the wave vectors describing the spin-wave modes is more complicated because of the localized nature of the modes (see discussion below). The collection angle of the scattered light was chosen small enough to ensure a reasonable resolution in $q_{\|}$ of $\pm 0.8 \times 10^4$ cm^{-1}. At small angles of light incidence the directly reflected beam and diffraction reflexes entering the collection lens were blocked by small blinds inserted into the collection aperture.

Figure 1 shows the anti-Stokes side of a typical Brillouin light scattering spectrum for a transferred wave

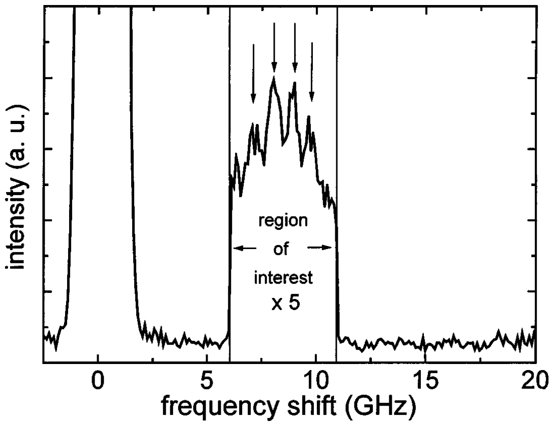

FIG. 1. Brillouin light scattering spectrum of the sample with a wire width of 1.8 μm and a wire separation of 0.7 μm, demonstrating the existence of several discrete spin-wave modes with a mode splitting of about 0.9 GHz (indicated by arrows). The applied field is 0.5 kOe. The transferred in-plane wave vector $q_{\|}$ is $0.3 \times 10^5\ \mathrm{cm}^{-1}$. The intensity at zero frequency shift is due to elastically scattered light. In the region of interest, the scan speed is reduced by a factor of 5.

vector $q_{\|} = 0.3 \times 10^5\ \mathrm{cm}^{-1}$ of the sample with 0.7 μm separation between the wires. Near 7.1, 8.0, 8.8, and 9.6 GHz four distinct modes of magnetic excitations are observed. By varying the magnitude of the wave vector $q_{\|}$, the spin-wave dispersion is obtained, as displayed in Fig. 2. Shown are the data for wires with a separation of 2.2 μm (top), 0.7 μm (middle), and, for reference, for a continuous film (bottom). In the region of low wave vectors the spin-wave modes show a disintegration of the continuous dispersion of the Damon-Eshbach mode into several discrete, resonancelike modes. There is no significant difference between the data obtained from the wires with 0.7 and 2.2 μm separation, indicating that the mode splitting is purely caused by the quantization of the spin waves due to the finite wire width, and the magneto-dipole interaction between wires is small for both separations studied.

Studying the experimentally observed spin-wave dispersion of the patterned structures in more detail we note the following: (i) For low wave-vector values ($\cong 0-1.0 \times 10^5\ \mathrm{cm}^{-1}$) the discrete modes do not show any noticeable dispersion and they behave like standing wave resonances. (ii) The discrete modes are each observed over a continuous range of the transferred wave vector $q_{\|}$. (iii) The lowest mode appears near zero wave vector ($|q_{\|}| \leq 0.08 \times 10^5\ \mathrm{cm}^{-1}$), whereas all higher modes appear at higher wave vectors, and the value of the respective lower "cutoff" wave vector increases with the mode number. (iv) There is a transition region ($q_{\|} \cong 1.0 - 1.3 \times 10^5\ \mathrm{cm}^{-1}$) between the well-resolved dispersionless modes, and the continuous filmlike dispersion, where discrete modes exist, but the mode separation is close to or slightly below the experimental frequency resolution in the BLS experiment (≈ 0.1 GHz). (v) For large values of the wave vector ($q_{\|} > 1.3 \times 10^5\ \mathrm{cm}^{-1}$), the dispersion of the patterned film converges to the dispersion of a continuous film.

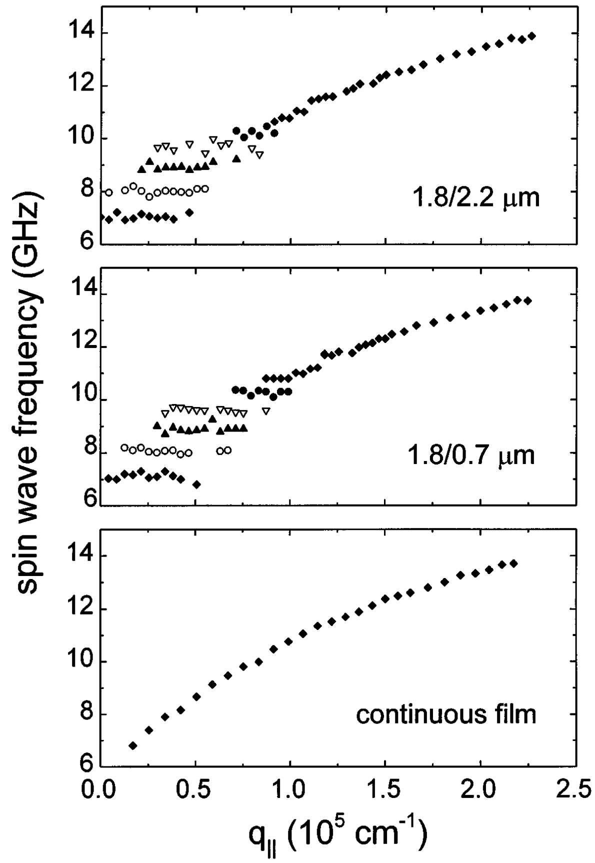

FIG. 2. Obtained spin-wave dispersion curves for an array of wires of 1.8 μm width and a separation of the wires of 2.2 μm (top) and 0.7 μm (middle). The bottom panel shows a spin-wave spectrum of a continuous film for reference. The thickness of the wires and the continuous film is 200 Å; the external field applied along the wire axes is 0.5 kOe.

It is worth noting that an early indication of the existence of discrete modes in the spin-wave spectrum of an array of permalloy wires was reported by Gurney *et al.* [8]. Three discrete spin-wave modes were observed at a single value of the in-plane wave vector $q_{\|} = 1.2 \times 10^5\ \mathrm{cm}^{-1}$. The authors of Ref. [8] were not able to identify the nature of the modes.

In order to understand the experimental results, the main issues are (i) to calculate the mode frequencies and (ii) to understand why each of the modes is observed over a characteristic continuous range of wave vectors. For the discussion we assume a Cartesian coordinate system oriented such that the normal of the pattern area points into the x direction, the wave vector $q_{\|}$ points into the y direction, and the wire axes, the applied magnetic field, and the magnetization are all aligned parallel to the z axis.

The discrete mode spectrum indicates a quantization due to the finite width of the wires. We assume a standing lateral wave pattern for the spin-wave modes with wavelength λ_n

$$w = n\,\frac{\lambda_n}{2}\,; \qquad q_{\parallel,n} \equiv \frac{2\pi}{\lambda_n} = \frac{\pi}{w}\,n\,, \tag{1}$$

with n the mode index, $n = 0, 1, 2 \ldots$, and w the wire width. The mode frequencies are obtained by inserting the discrete values $q_{\parallel,n}$ into the well-known Damon-Eshbach dispersion equation for dipolar surface spin waves in a film of thickness d [6]:

$$\nu_n = \frac{\gamma}{2\pi}\{H(H + 4\pi M_S) + (2\pi M_S)^2 \times [1 - \exp(-2q_{\parallel,n}d)]\}^{1/2}, \tag{2}$$

where H is the applied magnetic field, M_S is the saturation magnetization, and γ is the gyro-magnetic ratio. This approach should yield reasonable estimates for the frequencies of the quantized modes since the film thickness is much smaller than the width of the wires, and peculiarities at the wire side walls, like the appearance of edge or corner modes [9], are not important. For the calculation we use $H = 0.5$ kOe, the sample geometry parameters $d = 200$ Å, $w = 1.8\ \mu$m, and the independently measured values of the material parameters $4\pi M_S = 10.2$ kG, $\gamma/2\pi = 2.95$ GHz/kOe. The results of the calculation are shown in Fig. 3 by solid horizontal lines together with the experimental data. Without any fit parameters the calculation reproduces all mode frequencies with $n > 0$ very well, and for the $n = 0$ mode a reasonable agreement is achieved.

We note here that in Eq. (1) we assume no pinning of the spins at the side walls of the wires. This assumption is justified since anisotropies in permalloy are small. On the contrary, when pinning is active, a boundary condition analogous to the Rado-Weertman boundary condition of an infinite film must be imposed at the side walls, which results in a phase shift of the spin waves upon reflection of the side walls [10,11]. Indeed, by using a modified boundary condition [12] and by adjusting a suitably defined pinning parameter, we have obtained a slightly better fit for the $n = 0$ mode, while the higher order modes are almost not affected. The details will be reported elsewhere [12].

We note that the frequency separation $\Delta\nu = \nu_{n+1} - \nu_n$ of the discrete modes, as observed in our experiment, decreases with increasing wave number, $q_{\parallel,n}$, in agreement with our calculation. Thus the frequency splitting of neighboring discrete spin-wave modes, which are equally separated in the q space ($q_{\parallel,n} = n\pi/w$), becomes smaller with increasing wave vector until the mode separation is smaller than the frequency resolution in the BLS experiment and/or the natural line width and the splitting is not observable anymore. In this regime the observed spin-wave spectrum is well described by the dispersion equation for a film of infinite width and continuous values of $q_\parallel$ [Eq. (2)] with the same set of the parameters as has been used for the calculations of the quantized mode frequencies.

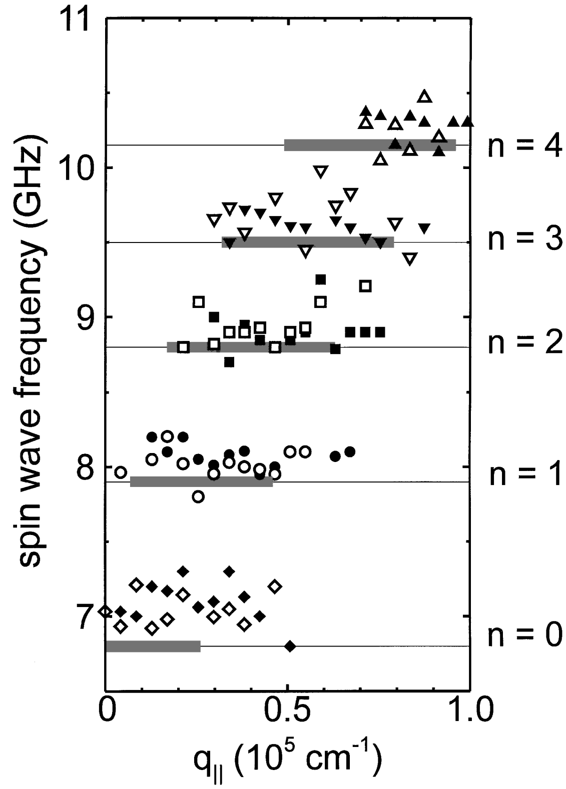

FIG. 3. Comparison of the measured mode frequencies for the wire arrays with separations of 0.7 μm (full symbols) and 2.2 μm (open symbols) with the calculated frequencies (horizontal lines), shown for the five lowest-order quantized surface spin-wave modes. The gray bars indicate the calculated wave-vector regions of observability of the discrete modes, as discussed in the text.

Finally, we discuss the experimental results of a finite, but continuous transferred wave-vector range of observation for each of the discrete modes. It can be understood as follows: In the light scattering experiment the parallel component of the wave vector $q_\parallel$ is conserved if the light is scattered by a plane wave traveling along the infinite surface. In our experiment, the width of each magnetic wire is small; i.e., it is comparable with the wavelength of the lateral standing modes causing the light scattering. The lack of dispersion of each discrete mode and the fact that the frequencies of the modes for both arrays with different distances between the wires are essentially the same indicate that each wire acts as an independent scatterer in the light scattering process. The spin-wave modes are then described by truncated plane waves, since the dynamic part of the magnetization $m_n(y)$ is zero outside the wire. For these modes the wave vector is not conserved anymore in the light scattering process, and the light scattering intensity is determined by the Fourier transform $m_n(q_\parallel)$ of $m_n(y)$: $I \propto |m_n(q_\parallel)|^2$ [13]. Since $m_n(y)$ is not a periodic function due to the truncation, the Fourier transform $m_n(q_\parallel)$ is nonzero over a continuous range of $q_\parallel$, resulting in a continuous range of wave-vector transfers in the inelastic light scattering process, where the mode is observed. For the calculation of $m_n(q_\parallel)$, we have assumed a cosinusoidal variation of the dynamic magnetization inside each wire, corresponding to unpinned modes. In Fig. 3 the intervals, where $|m_n(q_\parallel)|^2$ exceeds 10% of its maximum value, i.e., where the corresponding discrete mode contributes considerably to the light scattering cross section, are indicated by gray horizontal bars. There is a good agreement between the results of this calculation and the wave-vector intervals, in which the discrete modes are observed in our experiment [14].

In summary, we have observed a spin-wave mode quantization effect in a periodic array of magnetic wires. The observed discrete modes can be interpreted as resulting from the width-dependent quantization of the dipole-dominated surface spin-wave mode (quasi-Damon-Eshbach mode) of an infinite film. Both the frequency positions and the wave-vector intervals, where the discrete modes are observed, support our interpretation. For larger wave vectors a quasi-continuous spin-wave dispersion resembling closely the dispersion of a continuous film is obtained. No indication for a zone folding effect due to the periodic arrangement of the wires was found.

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