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Standing spin waves in perpendicularly magnetized circular dots at millimeter waves

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Spin wave spectra of 40-nm thick perpendicularly magnetized circular Permalloy dots of 250 nm radius were measured using ferromagnetic resonance technique in 70-80 GHz range at 4.2 K and in 10 GHz at room temperature. The five sharp resonance peaks were observed for both frequency ranges. The resonance fields can be well described by a magneto-exchange dispersion relation, implying that the observed resonances correspond to circular "drumhead" modes with Bessel-function profiles. The relative distances between neighbor peaks for different frequency ranges were almost the same, while the absolute interpeak distances in millimeter range were ~30% bigger than at 10 GHz, as predicted by the theory. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4799528]

INTRODUCTION

Further development of magnetic recording requires significant increase of read-write rates; therefore, it is important to probe magnetodynamical response of different perspective recording media at higher frequencies. Nowadays, patterned magnetic media (i.e., periodic arrays of patterned magnetic elements) is considered to the most promising technology as a solution to overcome the limits of conventional continuous magnetic media, such as superparamagnetic effect and medium noise.[1]

Recently, a lot of attention was paid to both the experimental and theoretical investigations of standing spin waves in submicron patterned magnetic elements. They were probed experimentally by Brillouin light scattering,[2,3] time resolved Kerr magneto-optics,[4,5] and ferromagnetic resonance (FMR). Particularly, interesting case is perpendicularly magnetized flat circular discs, since for this shape and geometry it is possible to describe spin-wave spectra with relatively simple analytical formulas. The most efficient experimental technique to study the perpendicular geometry is FMR, either cavity-based,[6,7] broadband,[8] or ferromagnetic resonance force microscopy.[9,10]

Up to now, experimental studies were limited by frequency range of 3–30 GHz. In this paper, the spin wave spectra of the periodic arrays of Permalloy submicron dots were measured at 4.2 K using FMR spectrometer operating in the 70–80 GHz frequency range, which corresponds to millimeter wave frequencies. The obtained results were compared with the ones measured at 10 GHz using commercial cavity-based electron spin resonance spectrometer.

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EXPERIMENTAL DETAILS

Square array of Py dots (2000×2000 elements) with radii $R = 250$ nm and thickness $L = 40$ nm was prepared on Si wafer with oxidized surface by means of electron-beam lithography and lift-off technique using Raith 150 electron-beam writer. The interdot center-to-center distance was fixed to $4R = 1000$ nm to exclude the influence of interdot magnetostatic interactions on the results. Py films were deposited using molecular-beam epitaxy in the vacuum 10^{-8} mbar. To improve the magnetic film quality, 2 nm Cr underlayer was deposited on Si/SiO_2 prior to Py growth. To protect the patterned samples from oxidation, they were covered by 2 nm Al layer. After removing resist, dot quality was checked by scanning electron microscopy.

The millimeter-wave FMR measurements were performed in the 72–77 GHz frequency range at 4.2 K using the experimental radiophysical complex "Buran" at the Institute of Radiophysics and Electronics NAS of Ukraine.[11,12] Two-mirror open resonator consisting of flat and spherical mirrors as a magnetoresonance cell in millimeter waveband was used. Mirrors were connected to the rectangular waveguide with a coupling slot. The diameter of each mirror was 30 mm, and the distance between the mirrors can be varied within 10–20 mm. The organic chemical compound 2,2-diphenyl-1-picrylhydrazyl (DPPH) was located in the vicinity of the sample to precisely measure the external magnetic field, generated by superconducting magnet (up to 75 kOe). This field was oriented along the normal to the sample.

The centimeter wave FMR measurements were performed at room temperature and fixed frequency of 9.85 GHz using a standard electron spin resonance spectrometer Bruker ELEXYS 500. Computer controlled goniometer was used to adjust an out-of-plane angle between the external magnetic field and normal to the sample plane.

RESULTS AND DISCUSSION

The millimeter-wave measurements were performed at different frequencies f from 72 to 77 GHz. DC magnetic field was swept from 20 to 40 kOe. Five resonance peaks were clearly observed above sharp intense peak from DPPH peak, and their intensities increased with field (see Fig. 1). Distances between neighbor peaks did not change in the measured range (Fig. 2). Having in mind that gyromagnetic ratio of DPPH g = 2.0036 is known with very high accuracy, its $f_{res}(H_{res})$ dependence in 72–77 GHz range was used to calibrate the dc field generated by superconducted magnet.

The spin-wave spectrum at 10 GHz had exactly the same structure as the ones obtained at millimeter waves (Fig. 3(a)). It also consisted of five rather sharp peaks with intensities gradually increased with field. The structure of the spectra in different frequency ranges (i.e., relative distances between neighbor peaks) was found to be the same; however, the inter-peak distances at 75 GHz were ~30% bigger than at 10 GHz.

One may observe that the signal-to-noise ratio of centimeter wave spectra is significantly higher than the millimeter wave ones. It is mostly due to the fact that the commercial ESR is using field modulation to measure microwave absorption derivative when the home-build millimeter wave system is measuring absorption. Therefore, it would be extremely useful to equip "Buran" with field modulation option. Also, the quality factor of the X-band closed rectangular cavity is higher than the one of two-mirror open cavity. However, the number of standing spin wave modes detected by both systems is the same.

Spin wave resonance frequencies for the dot array under study were calculated on the basis of the theory developed in Ref. 13. For the lowest (uniform along the film thickness) spin wave mode of a perpendicularly magnetized film of the thickness L, an approximate diagonal dipole-exchange spin wave dispersion equation can be written as

$$\omega_k^2 = (\omega_H + \alpha\omega_M k^2)\big(\omega_H + \alpha\omega_M k^2 + \omega_M \mu(kL)\big).$$

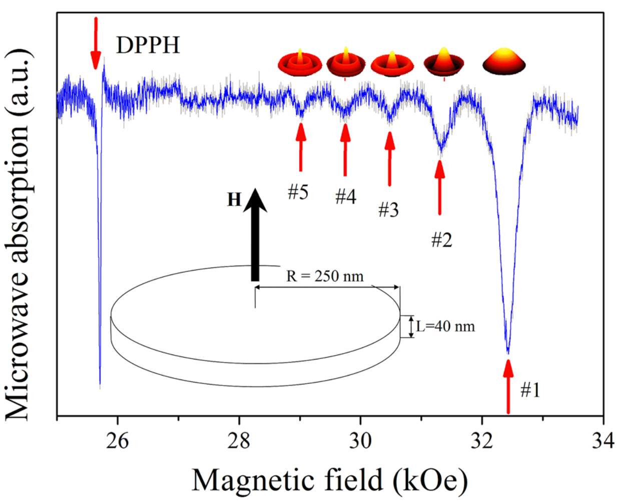

FIG. 1. Experimental spectra of array of circular Permalloy dots at 72.5 GHz. The inset shows disc dimensions and orientation of external magnetic field. Profiles of zero-order Bessel functions are shown above corresponding resonance peaks.

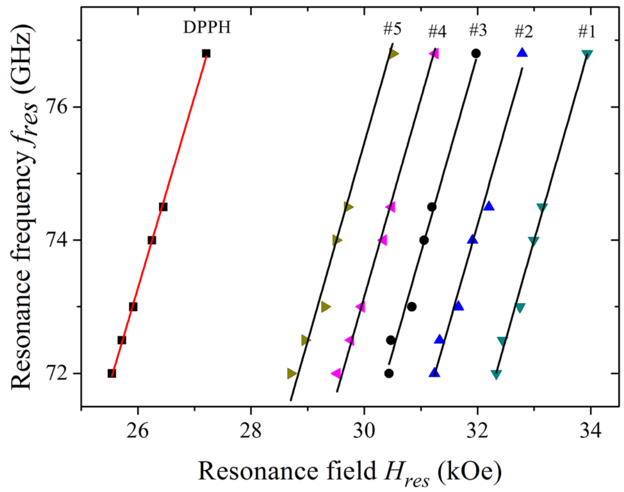

FIG. 2. Dependences $f_{res}(H_{res})$ for different standing spin-wave modes at millimeter waves. Black lines are fits using analytical theory[13] with $\gamma/2\pi = 2.96$ MHz/Oe and $M_s = 795$ G.

Here, $\omega_H = \gamma H_i$, where the internal field $H_i = H - 4\pi M_s$, H is the applied field, and M_s is the saturation magnetization of the film, γ denotes the gyromagnetic ratio, $\omega_M = 4\pi\gamma M_s$, $\alpha = A/2\pi M_s^2$ is the exchange constant, and A is the exchange stiffness constant. k is the modulus of the in-plane spin-wave wave vector, and $\mu(kL) = 1 - (1 - \exp(-kL))/kL$ is the matrix element of the dipole–dipole interaction for a perpendicularly

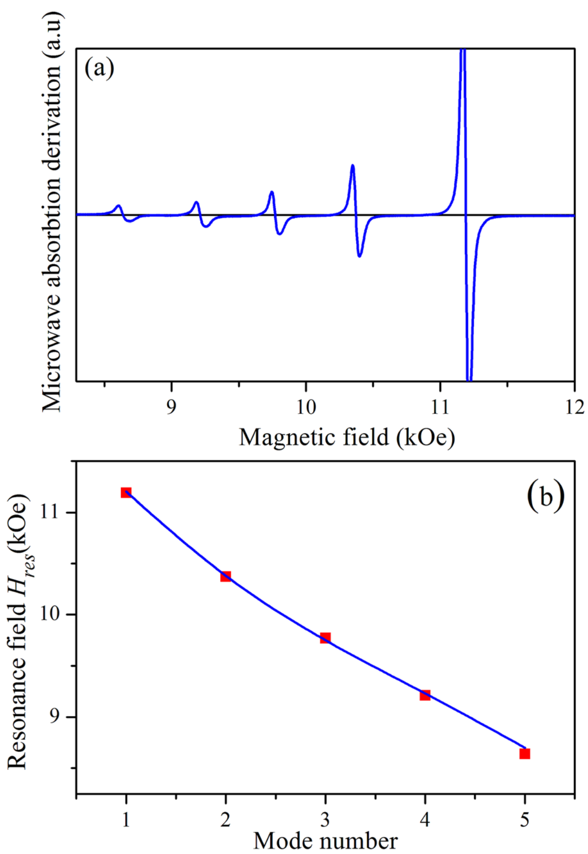

FIG. 3. (a) Experimental spectra of array of circular Permalloy dots at 9.86 GHz. (b) Dependence of the resonance field on the mode number. Points are experimental data, line is a fit using analytical theory[13] with $\gamma/2\pi = 2.965$ MHz/Oe and $M_s = 765$ G.

magnetized film. With two adjustments, the above equation can be used to describe approximately the frequencies of standing in-plane spin wave modes in a magnetic dot having the shape of a thin disk of radius R (case $L/R \ll 1$). First, due to the finite radius of the disk, only discrete values on the in-plane wave vector will be allowed $k \rightarrow k_m$, where $m = 1, 2, 3, \ldots$ is the radial mode number, i.e., we shall have the dot standing spin wave modes having quantized values of the in-plane wave number. Assuming dipolar pinning on the dot edges and zeroth-order Bessel function mode profiles, the following condition for the in-plane wave vector can be written: $k_m = \beta_m/R$, where the β_m are the roots of the zeroth-order Bessel function. Second, due to the nonellipsoidal shape of the dot demagnetizing field inside the dot will be inhomogeneous, and the internal bias field will be a function of the radial coordinate ρ: $H_i(\rho) = H - 4\pi M_s N(\rho)$. Since the different standing modes in the dot have different radial profiles, the averaged internal bias magnetic field will be different for different modes: $H_i = H - 4\pi M_s N_m$, where N_m is the effective matrix elements of the inhomogeneous demagnetizing field (see formulas (4) and (5) in Ref. 13). For the investigated dots, $H_i = H$—9990 Oe; $H_{i1} = H$—8990 Oe, $H_{i2} = H$—8800 Oe, $H_{i3} = H$—8730 Oe.

In the case of millimeter wave measurements, we were able to fit all the $f(H_{res,m})$ dependencies simultaneously (Fig. 2). The best fit was obtained for the pair of fitting parameters $\gamma/2\pi = 2.96$ MHz/Oe and $M_s = 795$ G, the value of exchange stiffness constant A was fixed at tabular value for Permalloy 1.3×10^{-6} erg/cm. It is very important to underline that these are the typical parameters for Permalloy. In case of 10 GHz measurements, the best fit was obtained for almost the same value of $\gamma/2\pi = 2.97$ MHz/Oe but with a bit lower value of $M_s = 765$ G (Fig. 3(b)). This 30 G difference was explained by different experiment temperatures, 4.2 K for millimeter and 300 K for centimeter waves, so there is no surprise that saturation magnetization is slightly decreasing with temperature increase.

These results clearly demonstrate that the fitting of the spin-wave spectra of the perpendicularly magnetized circular dot array can provide precise information about gyromagnetic ratio and saturation magnetization of the magnetic material. Of course, it is very important to have an array of non-interacting dots, otherwise the dipolar interactions will contribute to the internal field H_i and this will increase the measured M_s. However, to avoid this error, it is enough to use square arrays with interdot center-to-center distances of 4R, in this case dipolar interactions became negligible.[14]

Another important result of this comparative study is that the analytical theory[13] proved its effectiveness up to the 80 GHz and down to 4.2 K. The predicted increase of interpeak distances with the frequency rise was confirmed experimentally with high accuracy, no qualitative change of the spin wave spectra behavior at high frequencies, and low temperatures was observed.

CONCLUSIONS

The comparative study of spin-wave spectra of perpendicularly magnetized array of submicron circular Permalloy dots at millimeter and centimeter waves demonstrated that

(a) The structure of the spectra (number of peaks and relative distances between neighbor peaks) in different frequency ranges is the same; however, the interpeak distances are increasing with frequency increase.
(b) Previously developed analytical theory that take into account strong pinning of dynamical magnetization on the dot edges and different demagnetizing factors for different modes proved its effectiveness up to the 80 GHz and down to 4.2 K.
(c) Fitting of the spectra using this theory can provide precise information about gyromagnetic ratio and saturation magnetization of the magnetic material.

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