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Time resolved studies of edge modes in magnetic nanoelements (invited)

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Micromagnetic simulations have been performed to investigate the frequencies and relative amplitudes of resonant magnetic modes within nanomagnetic elements of varying size that have been previously studied by time resolved Kerr magnetometry. The magnetic response of a nanoscale element generally consists of the edge and center localized modes. For 2.5 nm thick elements, a crossover from center to edge mode excitation occurs as the element size is reduced to less than 220 nm. Additional modes appear in the spin wave spectrum as the thickness of the element is increased. The frequency of the edge mode is particularly sensitive to the strength of the exchange interaction, dipolar interactions with nearest neighbor elements, and rounding of the corners of the element. Simulations with in-plane pulsed fields show that the edge mode becomes dominant in elements of somewhat larger size, emphasizing the importance of the edge mode in technological applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2177346]

I. INTRODUCTION

The picosecond magnetization dynamics of small magnetic elements underpin the operation of future recording head sensors, magnetic random access memory, and spin-torque devices. The nonuniform demagnetization field and magnetization in nonellipsoidal elements lead to an inherently nonuniform dynamics. Magnetic reorientation induced by a pulsed magnetic field can then be understood in terms of the excitation and dephasing of resonant modes that may be confined by the nonuniform demagnetizing field. The mode spectra in nanometer and micron sized magnetic elements should be different due to the increased importance of the exchange interaction as the element size is reduced. In particular, at a finite bias field (e.g., as used in biased magnetic field sensors), the magnetization response of a magnetic element to a pulsed magnetic field of short rise time might be expected to become more uniform as the element dimensions approach the exchange length. Indeed uniform magnetization dynamics are preferred in data storage technology in order to achieve higher recording densities.

In contrast to studies of micron sized elements, where techniques such as time resolved scanning Kerr microscopy (TRSKM),[1–11] spatially resolved Brillouin light scattering (BLS),[10] wide-field Kerr microscopy,[12] x-ray magnetic circular dichroism (XMCD) transmission microscopy,[13] and XMCD photoelectron emission microscopy[14,15] (PEEM) have been successfully applied, the spatial character of the magnetization dynamics in submicron sized elements remains virtually unexplored experimentally. The lack of nanoscale spatial resolution has been circumvented by measuring the frequency[16–21] or time[22,23] domain response from sufficiently large arrays of nanomagnets and comparing the measured signals with analytical theories[18–20] and/or micromagnetic simulations.[16,17,21–29] In particular, this approach has led to the discovery of a crossover from a center to edge localized mode as the magnetic element size is reduced to less than 220 nm.[22,23]

In this paper, numerical simulations performed with the object oriented micromagnetic framework[30] (OOMMF) have been used to study various factors affecting the high frequency response of the nanoscale magnetic elements, and the degree to which such simulations can reproduce the data reported in Refs. 22 and 23. OOMMF simulations with harmonic magnetic field excitation have been used to confirm the spatial character of the observed modes.

II. DETAILS OF THE SIMULATIONS

Numerical simulations were performed with the parameter values determined experimentally in Ref. 22 and used in the simulations of Ref. 23. The sizes (edge to edge separations) of the square of 24.9 Å thick elements were assumed to be 630 (37.5), 426 (18), 220 (95), 120 (36) and 64 (48.64) nm. The value of the saturation magnetization was 930 emu/cm^3, while a value of 2.1 was assumed for the g factor. The uniaxial and surface anisotropy parameters had values of 4140 ± 330 erg/cm^3 and 0.156 ± 0.022 erg/cm^2, while the in-plane easy axis was canted by about 10° from the element edge. Each sample was divided into square cells with height equal to the element thickness, while the lateral cell size was 7.5, 6, 5, 4, and 2.56 nm for the 630, 426, 220, 120, and 64 nm element arrays, respectively.

The static configuration at each bias field value was prepared by allowing the magnetization to relax from the uniformly magnetized state. This static state was then used as the initial configuration in two kinds of dynamical simulation. First, an out-of-plane pulsed field with 40 ps rise time, 2 ns decay time, and magnitude of 15 Oe was applied to the sample. Second, a harmonic out-of-plane field with ampli-

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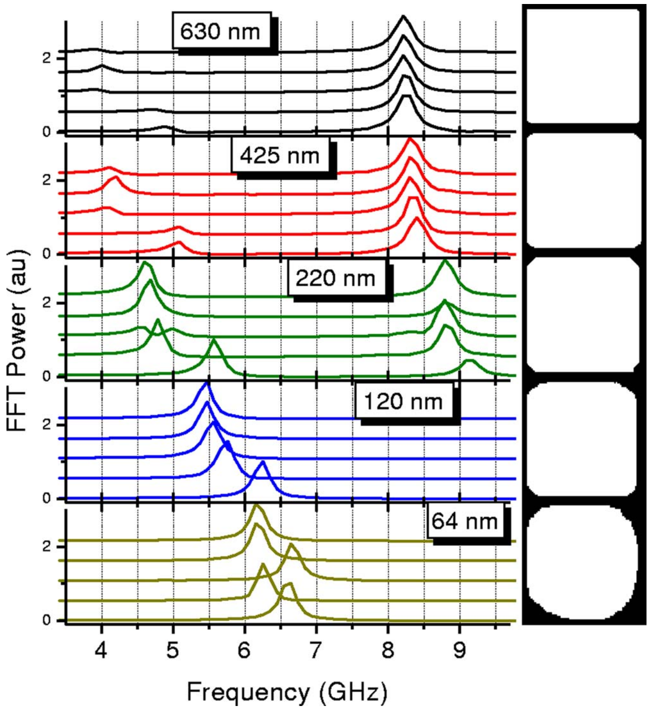

FIG. 1. (Color online) In the left column, FFT power spectra of simulated time resolved signals are presented for elements of different sizes for the field value of 772 Oe. In each set of spectra, curves from top to bottom correspond to simulations for (a) a single perfect square element with out-of-plane pulsed field, (b) a single perfect square element with in-plane pulsed field, (c) a single element of realistic shape with out-of-plane pulsed field, (d) the center element from a 3×3 array of perfect square elements with out-of-plane pulsed field, and (e) a single perfect square element with exchange parameter value increased by 50% and with out-of-plane pulsed field. In the right column, the images of the elements used in the simulations with realistic shape (c) are shown. The images were obtained from SEM images by changing their contrast from gray scale to black and white.

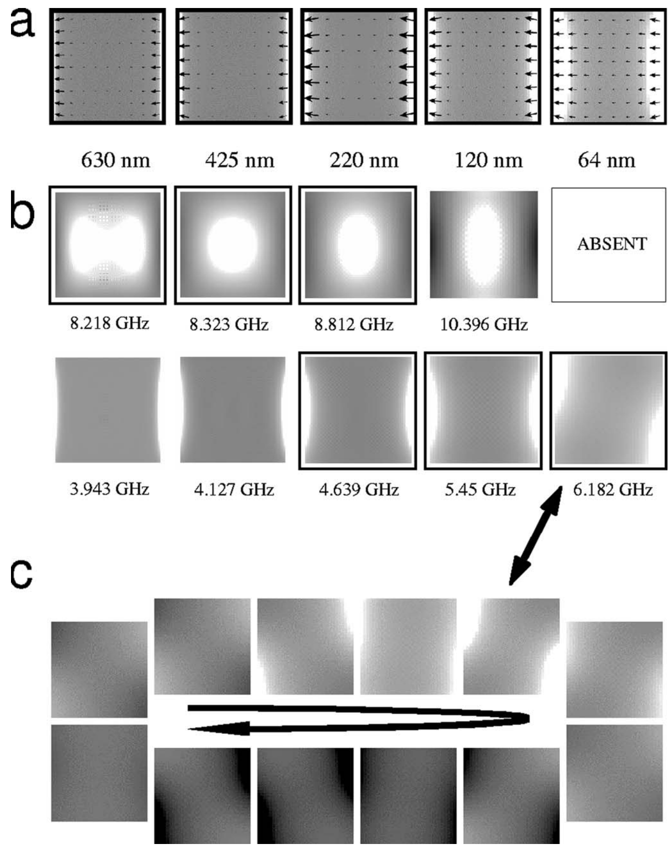

FIG. 3. (a) The calculated spatial distribution of the horizontal component of the demagnetizing field is shown. (b) The simulated spatial distribution of the out-of-plane component of the dynamic magnetization in response to harmonic excitation is shown for the elements of different sizes. The top and bottom rows correspond to the center and edge localized modes, respectively. (c) The full cycle of precession is shown as simulated for the edge mode of the 64 nm element. The time delay between subsequent images is about 15 ps. The white and the black of the grey scale correspond to the maximum and minimum values of the dynamic magnetization, respectively. The bias magnetic field is horizontal.

tude of 15 Oe and frequency corresponding to one of the modes identified from the response to the pulsed excitation was applied. In both types of simulation, the dynamic magnetic state was recorded at regular intervals after the beginning of the excitation. Here, we will discuss only those modes from the simulations that have the largest amplitudes and hence correspond to those observed in our previous experiments, i.e., the center mode for the 220, 425, and 630 nm elements, and the edge mode for the 64, 120, and 220 nm elements. For a more complete numerical discussion of the possible normal modes of perfect magnetic nanoelements, we refer the reader to Refs. 24–29.

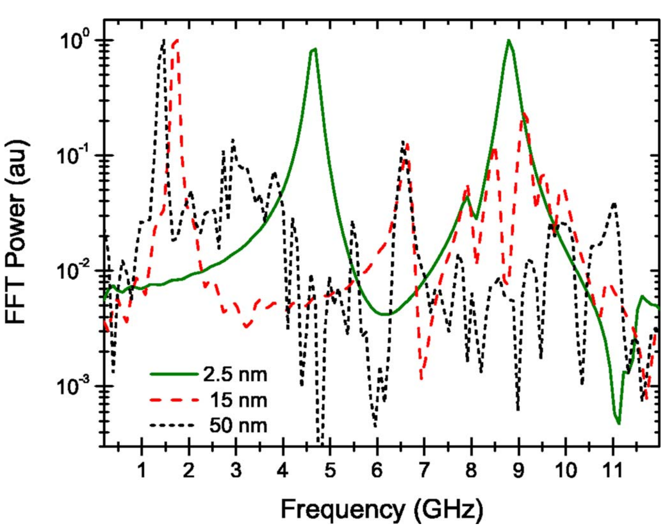

FIG. 2. (Color online) The simulated FFT spectra for 220 nm perfect square elements of different thicknesses are shown for the bias field value of 772 Oe.

III. NUMERICAL RESULTS

The fast Fourier transform (FFT) spectra calculated from the simulated response of elements of different sizes using different models are compared in Figs. 1 and 2 for the bias magnetic field value of 772 Oe. Figure 3 presents the spatial character of the modes observed in the simulations.

A. Orientation of pulsed field

The static magnetization in nonellipsoidal elements is nonuniform, but normally lies within the plane of the element. The pulsed field used to operate magnetic elements in real devices is also more likely to be applied in plane of the element. When the pulsed field is out of plane the initial torque acting upon the magnetization is uniform in magnitude but nonuniform in direction.[3] However, when the pulsed field is in plane, the initial torque may also be nonuniform in magnitude.[3] Therefore pulsed fields of different orientations may in principle give rise to modes of different spatial characters. In addition, the in-plane pulsed field may affect the value of the mode frequency.[3,4]

However, as seen from Fig. 1, the simulations of the response of the same individual perfectly shaped square elements to the in-plane and out-of-plane pulsed fields gave rather similar results with a somewhat increased edge to center mode amplitude ratio in the case of the in-plane excitation. This implies that the nonuniformity of the magnetization dynamics reported in Ref. 23 should also be observed when the pulsed field is applied in plane, as is the case in various technological applications.

B. Element shape

The shape of real elements is always imperfect. To study the effects associated with the edge roughness, we have performed simulations with an out-of-plane pulsed field for individual elements with shape determined from scanning electron microscopy (SEM) images of real elements, as shown in the right column of Fig. 1.

From Fig. 1, the element shape is found to have a greater effect upon the mode frequency than the pulsed field orientation. While the center mode frequency was almost unaffected, the edge mode frequency increased as the element shape diverged from ideal, with the largest increase observed for the 64 nm element. The edge mode of the 220 nm element was observed to split into two modes of smaller amplitude.

C. Interelement interaction

The effects of the interaction between different elements within an array have been studied by analyzing the response to an out-of-plane field of the center element within model 3×3 arrays of perfect square elements separated as in Refs. 22 and 23. From Fig. 1 the interaction between elements within the array is seen to affect the edge mode more significantly than the center mode. This is because the stray dipolar fields are nonuniform and falloff very rapidly on the length scale of the element size. Note that this result is distinctly different from that in Ref. 20, in which arrays of out-of-plane magnetized circular dots were studied. The authors of Ref. 20 concluded that "the dipole-dipole interaction between dots, which is significant for small interdot intervals, shifts the observed spectra as a whole, but did not change the structure of the spectra and relative positions of the corresponding resonance peaks."

D. Exchange constant

The value of the exchange parameter for the $Co_{80}Fe_{20}$ alloy was unknown and could not be deduced from preliminary measurements of the uniform response of the 10 μm square element in Ref. 22. Therefore, the exchange parameter of Permalloy was taken for the simulations presented in Ref. 23. Here, the effect of the exchange parameter value has been tested by performing simulations with an out-of-plane pulsed field for single perfect square elements with an exchange parameter that has been increased in value by 50%. Figure 1 again shows that the increased exchange parameter value has a much more significant impact upon the edge mode, which is explained by its stronger confinement.

E. Element thickness

While the aspect ratio and shape determine the dipolar energy of the element, its size and thickness determine the length scale for the excited magnetization dynamics and hence the exchange energy. Figure 2 shows the simulated FFT spectra for 220 nm perfect square elements of different thicknesses at the same bias field value of 772 Oe. The increased thickness and hence reduced aspect ratio of the elements result in a very rich spectrum of spin wave modes. Such modes are normally localized in the center of the element, and constitute the primary subject of investigation in Refs. 16 and 19–21. The reduced thickness, and hence the increased aspect ratio, of our samples leads to a smaller frequency splitting of these modes,[5] which hence superpose to give the center localized mode in the present study.

F. Spatial character

The spatial character of the different observed modes can be determined from the simulations performed with harmonic excitation.[16] Figure 3(b) shows the simulated spatial distribution of the out-of-plane component of the dynamic magnetization within isolated perfect square elements of different sizes assuming the exchange parameter value of Permalloy. The modes can be clearly grouped according to their spatial character as center and edge localized modes.[31] For the 425, 220, and 120 nm elements the region of localization of the center mode has a more or less regular oval shape, while it has a "dog bone" shape for the 630 nm element. This can be explained in terms of a superposition of the quasiuniform mode and a backward volume magnetostatic mode, both of which are localized in the central region of the element and have very similar frequencies. The center mode was absent for the 64 nm element. While for the 630, 425, 220, and 120 nm elements the edge mode is localized near the edges perpendicular to the bias field, it seems to have a "corner" character in the 64 nm element. However, the images for a full cycle of precession, which are shown in Fig. 3(c), reveal that for the 64 nm element there are actually two modes, one of which has the normal ("uniform") edge character, while the other has a node in the center of the edge and twice the frequency. Further simulations showed that the latter mode, which can be regarded as the first nonuniform mode of the edge region,[24] arises from a nonlinear process and disappears when the harmonic field amplitude is reduced.

IV. COMPARISON WITH EXPERIMENT

Using the knowledge acquired from the simulations described in the previous section, let us now try to simulate the experimental results reported in Refs. 22 and 23. Figure 4 compares the experimental spectra, obtained as described in Refs. 22 and 23 and in which both the edge and center modes

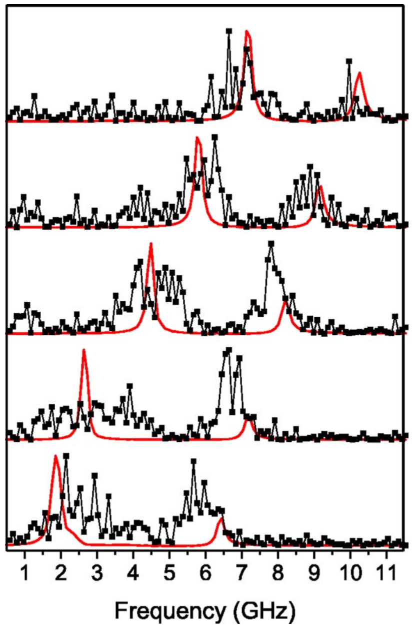

FIG. 4. (Color online) FFT power spectra of the measured and simulated time resolved signals are compared. The lines with symbols correspond to the experiment. The solid lines correspond to the simulations for a 3×3 array of realistically shaped squares with the exchange parameter value 50% larger than that of Permalloy. In each set, curves from top to bottom correspond to bias field values of 1000, 772, 589, 405, and 267 Oe, respectively.

are clearly observed, with those obtained numerically. In particular, we simulated the response to an out-of-plane field of the center element within a model of 3×3 array of realistically shaped 220 nm elements and with the value of the exchange parameter increased by 50%. The experimental and numerical results are seen to be in somewhat better agreement, compared to that in Ref. 23. The remaining discrepancy may result from two effects. Firstly, the magnetic parameters could have been modified during the patterning process, and this modification could be different for the nano- and microscale elements. Indeed, the agreement could be further enhanced if we tuned not only the exchange interaction parameter but also the surface anisotropy, for example. Secondly, the edge profile of the element may be important. For example, the element cross section could be more trapezoidal rather than rectangular. Micromagnetic simulations performed for a long wire of such cross section predicted that the edge mode frequency could be increased even further while the center mode frequency remained almost unaffected,[32] which is similar to the effect of using realistic element shapes considered here.

V. CONCLUSIONS

The magnetization dynamics of nanoscale magnetic elements were investigated by means of time resolved micromagnetic simulations. We found that, in contrast to the response observed in thicker elements, the response of nanoscale magnetic elements with thickness of just a few nanometers to a pulsed magnetic field is dominated by two modes localized in the edge and in the center of the element. As the element size is reduced, the edge mode becomes increasingly important and dominates the response of a 64 nm element. The interelement interaction and edge roughness primarily affect the edge mode, increasing its frequency, and become particularly important when the element size is reduced. Our results are important for technologies that exploit the high speed reorientation of the magnetization in nanoscale elements.

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[31] We note that, due to the highly nonuniform internal effective field, nanos-

cale magnetic elements with nonellipsoidal shape such as those studied here do not possess translational symmetry. Therefore, the mode wave number (linear momentum) is not a "good" quantum number, and so it is more appropriate to discuss the character of the modes in real rather than reciprocal space. Therefore, in the present work the term "localized" does not imply any particular property of the wave number, since no wave number either real or imaginary can be ascribed to the mode.
[32]R. D. McMichael (private communication).