Tunable spin wave dynamics in two-dimensional Ni$_{80}$Fe$_{20}$ nanodot lattices by varying dot shape

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We demonstrate tunable spin wave spectrum in two-dimensional Ni$_{80}$Fe$_{20}$ nanodot lattices by varying dot shape. A single collective mode in elliptical dot lattices transforms into three distinct modes for the half-elliptical, rectangular, and diamond dot lattices, albeit with different peak frequencies and intensities. A drastic change is observed for the triangular dots, where eight modes covering a broad band are observed. Using micromagnetic simulations, we characterized the modes as different localized, extended, and quantized modes, whose frequencies and spatial profiles are determined by a combination of internal field profiles within the nanodots and the stray magnetic field within the lattice. © 2014 AIP Publishing LLC.

Potential applications of nanomagnets in magnetic data storage, memory, and logic devices as well as in spin torque nano-oscillators as energy source and magnonic devices attracted interest into the ultrafast magnetization dynamics in the ferromagnetic nanostructures. The ever increasing demand of miniaturization and speed of devices offers challenges in controlling spin dynamics in ferromagnetic nanostructures by tailoring their physical structures and material parameters. These include size, shape, aspect ratio of the individual elements, and the periodic arrangements of the arrays. Arrays of confined magnetic dots show various static spin configurations due to a combination of internal field profiles and inter-element interaction. Consequently, the spin dynamics of such dots may be tuned significantly by varying the dot shape.

Recent developments made it possible to prepare nanostructures with various geometric shapes. Subsequently, significant research on understanding the spin configuration and investigation of quasistatic magnetization reversal mechanisms of nanoscale ferromagnetic nanodots with different shapes have been dedicated. In contrary, measurement and comparison of magnetization dynamics in ferromagnetic nanodots with varying geometric shapes are rare in the literature. Brillouin light scattering study of spin waves in triangular dot revealed localized modes, while elliptical dots with “egg-like” distortion showed splitting of end modes by asymmetric distortions causing inhomogeneous line broadening of that mode. Time-resolved magnetization dynamics study showed a three dimensional shape dependent spin wave modes. Using a similar method, a remarkable anisotropy in the nature and frequency of the spin wave mode was shown in a cross-shaped Ni$_{80}$Fe$_{20}$ nanoelement.

Here, we study the time-resolved magnetization dynamics of Ni$_{80}$Fe$_{20}$ nanodots with elliptical, half-elliptical, rectangular, diamond, and triangular shapes arranged in two dimensional square lattices. The dots are densely packed in the arrays to ensure that they are strongly magnetostatically coupled and show a collective magnetization dynamics. A simple square lattice is chosen to avoid exotic inter-dot interaction mediated by the dynamic stray magnetic field observed for different lattice symmetries. A remarkable change in the spin wave spectrum is observed with the dot shape. We used micromagnetic simulations to reproduce and interpret this variation of spin wave spectrum with the aid of the static magnetic configurations within the dots, stray magnetic field distributions within the arrays, and the simulated spin wave mode profiles.

Arrays covering 10 $\times$ 10 $\mu$m$^2$ area each of Ni$_{80}$Fe$_{20}$ dots with different shapes with 200 $\times$ 250 $\times$ 20 nm$^3$ ($x \times y \times z$) nominal dot dimensions and 75 nm nominal inter-dot separation between nearest edges were fabricated on self oxidized Si[100] substrate by a combination of electron beam lithography and electron-beam evaporation. A 3 nm thick Al$_2$O$_3$ layer was deposited on top of the Ni$_{80}$Fe$_{20}$ layer as a protective layer. The scanning electron micrographs of the fabricated samples are shown in Fig. 1(a), which shows that the shapes are reasonably well reproduced and the dimensions varying within about ±10% from the nominal dimensions. The thicknesses of the samples were found to be close to the nominal thickness from atomic force microscopy. The magnetization dynamics of the samples were measured by a custom built all-optical time-resolved magneto-optical Kerr effect (TR-MOKE) microscope using a two-color optical pump-probe (pump: $\lambda$ = 400 nm, pulsewidth = 100 fs, fluence = 15 mJ/cm$^2$, probe: $\lambda$ = 800 nm, pulsewidth = 70 fs, fluence = 2.5 mJ/cm$^2$) set-up. A bias magnetic field is applied at a small angle (~10°) to the sample plane, the in-plane component (along y-direction) of which is fixed at $H_z$ = 1.12 kOe for all measurements. The out-of-plane component of the bias field creates a finite demagnetizing field.
within the sample along the direction of the pump pulse, which is eventually modified by the pump pulse to induce a precessional motion of magnetization within the nanodots.

The time-resolved Kerr rotations for all lattices with different dot shapes and a Ni$_{80}$Fe$_{20}$ film of same thickness are shown in Fig. 1(b). The time-resolved data show an ultrafast demagnetization within about 500 fs, a fast relaxation ($\tau_1 \approx 1$ ps), and precession of magnetization superposed on a slow relaxation ($\tau_2 \approx 1$ ns) of magnetization. The demagnetization and the relaxation times are independent of dot shape, but the precessional dynamics vary significantly with the dot shape. The fast Fourier transform (FFT) of the time-resolved Kerr rotation after subtracting a bi-exponentially decaying background gives the spin wave spectrum for that sample.

Figure 2(a) shows the FFT power spectra obtained from the experimental data for samples with different dot shapes as shown in the inset of Fig. 2(a). The elliptical dot array shows a broad peak at 10.5 GHz with a small shoulder at 9.0 GHz. However, the half-elliptical shape shows three clear modes with a dominant mode at 11.3 GHz and two lower intensity modes at 9.0 and 5.1 GHz. The rectangular shape also shows three modes with the dominant one at 10.5 GHz and two lower intensity modes at 9.0 and 7.0 GHz. In the diamond shape, the highest frequency mode (13.4 GHz) has lower intensity, while mode 2 (12.0 GHz) has the highest intensity. In addition, there is a split and broad mode centred around 9.0 GHz. In contrary, the triangular shape shows eight modes covering a frequency range from 2.7 to 17.5 GHz for this bias field.

Micromagnetic simulations using OOMMF software on arrays of $7 \times 7$ dots with dot dimensions of about $200 \times 250 \times 20$ nm$^3$, inter-dot separation of about 75 nm, and with sample shapes derived from the SEM images are
shown in Fig. 2(b). The samples are divided into rectangular prism like cells with dimensions $3 \times 3 \times 20$ nm$^3$ so that the lateral dimensions of the cells are well below the exchange length ($l_{ex} \approx 5.3$ nm) for Ni$_{80}$Fe$_{20}$. The material parameters for Ni$_{80}$Fe$_{20}$ used in the simulations are gyromagnetic ratio $\gamma = 18.5$ MHz/Oe, anisotropy field $H_K = 0$ and saturation magnetization $M_S = 860$ emu/cc as extracted from the Kittel fit to the precession frequency vs. bias field for a Ni$_{80}$Fe$_{20}$ thin film. On the other hand, the exchange stiffness constant is used as $A = 1.3 \times 10^{-6}$ erg/cm as obtained from literature. The static magnetic configurations of $3 \times 3$ elements from the centre of the larger arrays are shown in the inset of Fig. 2(b). The simulated spin wave spectra (Fig. 2(b)) from the arrays of dots qualitatively reproduced the experimental modes. For the elliptical dot array, only a single sharp peak is observed in the spectrum, and no additional shoulder appears as opposed to the experimental spectrum. For the half-elliptical and rectangular arrays, three clear peaks resembling the experimental spectra are observed. The mode intensities for these two cases are also similar to the experimental spectra. For the diamond shaped dot array, three modes are observed with similar peak frequencies and intensities but a splitting of mode 1 is not reproduced in the simulated spectrum. In the triangular shaped dot array, a large number of modes covering a wide frequency range are observed, in which the experimentally observed modes (1 to 8) could be identified, although the relative mode intensities are not exactly reproduced and some additional small peaks are observed in the simulation, which remained un-resolved in the experimental spectrum. The demagnetized regions near the edges of the dots in the array for differently shaped dots indicate the non-uniform internal fields, which helped in forming the observed modes. In order to understand the effects of the inter-dot interactions on the modes, we also calculated the spin wave spectra of single nanodots with different shapes as shown in Fig. 2(c), with the static magnetic configurations shown at the insets. The static magnetic configurations do not vary significantly in the array. However, there are some remarkable differences in the spin wave spectra in the arrays as opposed to the single nanodots. Mode 1 of elliptical dots is suppressed in the array. Peak frequencies and intensities of modes 2 and 3 are strongly modified in the arrays for half-elliptical and rectangular dots. For the diamond shaped dot, only the widths of the peaks vary in the array, while peak frequencies and relative intensities remained unaffected. For the triangular shaped dot the peak positions and intensities are significantly modified in the array.

We have further calculated the spin wave mode profiles using a homegrown code. The power distributions of the modes for the single nanodots are shown in Fig. 3. Modes 1 and 2 for the single elliptical dot are well known edge mode and centre mode of the element. For the half-elliptical and rectangular dots, mode 1 is identified as the edge mode and mode 3 as the centre mode. However, near the base of the half elliptical dot and the horizontal edges of the rectangular dot, Damon-Eshbach (DE) mode with quantization number $n_{D} = 3$ is mixed with the centre mode. On the other hand, mode 2 is a mixed edge mode, and Damon-Eshbach (EM-DE) mode also observed previously for square dots. For the diamond shaped dot, all modes are standing spin wave modes in the backward volume magnetostatic (BWVMS) configuration. Here, modes 1, 2, and 3 correspond to the mode quantization number $n_B = 3$, 5, and 7, respectively. This means frequency increases with the mode quantization number and only odd (symmetric) modes are observed. The triangular dot shows more complicated mode structures as opposed to the other shapes. In this case, mode 1 is localized near the base of the triangle. Mode 2 extends from the base towards the vertex and form a standing wave pattern with quantization number $n_B = 2$ in the BWVMS geometry and also another standing wave pattern with $n_D = 2$ in the DE geometry. Modes 3 to 8 correspond to BWVMS mode with increasing $n_B$ from 3 to 8. However, they are mixed with DE modes with $n_D = 3$ for modes 3 to 7 and $n_D = 4$ for mode 8. The mode patterns deviate from a regular shape due to the deviation from the perfect geometric shape (rounded corners and fabrication induced asymmetry in the real samples). In the case of triangle, there is further asymmetry in the DE
modes due to the fact that the boundaries of the potential well where the modes are localized are not parallel to the y-axis, i.e., the direction of the applied bias field.

In the arrays, the modes are further modified as shown in Fig. 4. The single mode observed in the array of the elliptical dots show a standing wave pattern of BWVMS origin. The mode quantization number is greater near the edges of the array, which is probably due to the finite boundary of the array. Neither of the edge mode and centre mode of the single elliptical dot is observed in the collective dynamics of the array. In the arrays of half-elliptical and rectangular dots, modes 1 and 3 correspond to the coherent precession of modes 1 and 2 of the corresponding single dots over the entire array. However, mode 2 in both cases is the BWVMS like collective standing wave mode. In the array of diamond shaped dots, three modes are coherent precession in all dots in the array of modes 1, 2, and 3 of the single dots. The modes of the single dots are least affected due to the inter-dot interaction for this dot shape. The increase in linewidth of the modes is probably due to the small distribution in the dot shapes and sizes in the array, which caused an inhomogeneous line broadening for all three modes. For the triangular dot array, mode 1 corresponds to mode 1 of single triangular dot distributed primarily near the edges of the array, while mode 2 corresponds to the same mode of the single dot distributed over the entire array. This is why mode 2 of the array is more intense than mode 1. Modes 3 to 6 of the array correspond to nearly uniform distribution of modes 2 to 5 of the single triangular dots in the array. However, the mode structures are slightly modified in the array due to the inter-dot interaction. Mode 7 corresponds to a composite of modes 6 and 7 of the single triangular dots distributed randomly in the array. Mode 8 of the array corresponds to uniform distribution of mode 8 of the single dot, where the mode structures are again slightly modified in the array due to inter-dot interactions.

We have further calculated the magnetostatic field distribution in arrays with different dot shapes as shown in Fig. 5. The elliptical dots are strongly magnetostatically coupled ($H_g \approx 2.4 \text{ kOe}$ at the centre of the gap between two neighboring dots) and form a single collective BWVMS-like mode in the array, while the edge mode and centre mode of the single elliptical dot are suppressed. In the cases of half-elliptical dot array, the inter-dot interaction is sufficiently strong ($H_g \approx 1.61 \text{ kOe}$) to cause a different collective BWVMS like mode in the array and suppression of the EM-DE mode (mode 2) of the single dot. Mode 1 and mode 3 of the single dot survives in the array with modified spatial profiles. In the rectangular dot array, the inter-dot interaction is again quite strong ($H_g \approx 1.7 \text{ kOe}$), and only mode 1 (centre mode) of the single dot survives in the array. Mode 2 of the array is a collective BWVMS-like mode not observed in the single dot, while mode 3 is an edge mode with significantly modified profile as well as the mode frequency. The diamond shaped dot array shows a composite of modes 6 and 7 of the single dot, which is again modified due to the collective interaction.

![Figure 4](image1.png)

**FIG. 4.** Simulated spin wave mode profiles in arrays of nanodots with different shapes. The color scale for the power of the modes is shown at the right side of the figure. The mode numbers are given at the top of the mode profiles.

![Figure 5](image2.png)

**FIG. 5.** Simulated magnetostatic field distribution from the central part of the arrays of $7 \times 7$ dots with (a) elliptical, (b) half-elliptical, (c) rectangular, (d) diamond, and (e) triangular shape. The bias field of 1.12 kOe was applied along the y-axis. The arrows represent the magnetization within the elements, while the contours show the stray magnetic field distribution. The color scale for the contour map is shown.
dots are only weakly affected by the inter-dot interactions ($H_g \approx 0.65$ kOe) in the array and consequently, the modes retain their identities within the array barring the line broadening as explained earlier. In the triangular dots, again the interaction is moderate ($H_g \approx 0.71$ kOe) and primarily concentrates between the vertex of the lower triangle and the base of the upper triangle. Consequently, all modes are slightly modified but retained their identities in the array.

In summary, we have investigated the effects of dot shape on the ultrafast magnetization dynamics in $\text{Ni}_{80}\text{Fe}_{20}$ nanodot arrays with elliptical, half-elliptical, rectangular, diamond, and triangular shapes. The ultrafast demagnetization and relaxation times showed no significant dependence on the dot shape but the spin wave spectrum showed a strong dependence on the dot shape. While the elliptical dot array showed a single broad mode with a small shoulder, the half-elliptical, rectangular, and diamond shaped dot arrays showed three clear modes although with substantially different peak frequencies and a splitting in the lowest frequency mode for the diamond shaped dot. In contrary, the triangular dot array showed eight modes over a broad frequency range. Micromagnetic simulations reproduced the observed modes, and the simulated mode profiles showed primarily the edge mode and centre mode blended with DE-like standing wave modes in some cases. However, the diamond shaped dot showed only symmetric BWVMS-like standing wave modes, while the triangular dot showed mixed BWVMS-DE modes with varying mode numbers. However, the single nanodot modes often did not survive in the array, where different collective modes are formed due to strong inter-dot magnetostatic interaction, which is strongest in the elliptical dot array, where none of the single dot modes survived and weakest in the diamond shaped dot array, where all modes survived with least modifications. Such a wide variation in the spin wave mode spectrum and spatial profiles in single nanodots and their collective behaviour opens up additional possibilities for selection of building blocks for magnonic and spintronic devices.

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