COMPUTATION OF SPIN-WAVE SPECTRA OF MAGNETIC NANOSTRUCTURES FOR INFORMATION STORAGE SYSTEMS

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ABSTRACT

In recent years, micromagnetic simulation has evolved into a vital tool for understanding and optimizing the electronic and dynamic properties of magnetic structures on the nanometer scale. We have enhanced a micromagnetic simulation tool and developed a package called SpinWaveAnalyzer for the computation of the spin-wave spectra for arbitrary excitation patterns. We find that the spin-wave eigenmodes sensitively depend on the spatial symmetry of their excitations and that for decreasing lateral extensions, the oscillatory behaviour of nanosized multilayers shifts from standing spin waves with higher harmonics along and perpendicular to the static magnetization to dipolar modes with higher harmonics situated on the edge of a structure. These simulations can help to find the optimal frequency with which to switch the magnetization of real-life magnetic storage cells, thus enabling the creation of faster, non-volatile, low-power storage concepts that could revolutionize computer architectures.

INTRODUCTION

Magnetic storage systems have become indispensable due to their storage density, availability, reliability, and their low costs. The increase in information that can be stored on a unit area of magnetic storage surface has largely followed an exponential behaviour called Kryder's law, similar to the famous Moore's law for the number of transistors on a chip, but with larger exponent. Individual information bits are stored in regions of ferromagnetic grains of the same magnetization. Fundamentally limiting a continued exponential increase is the so-called superparamagnetic effect in which thermal fluctuations increasingly disturb the magnetization with decreasing size of the magnetic regions. An analytical model (Stoner and Wohlfarth 1948) can estimate the thermal stability of a region. The speed with which magnetic particles can switch their magnetization state is determined by the eigenfrequencies of the magnetic systems. Changes in the magnetization permeate through the system via discrete oscillations, called spin-waves, which can be attributed with a frequency and a wave vector. Predicting the eigenfrequencies of a given system with the help of micromagnetic simulations and subsequent spin-wave spectra can help to create faster, more reliable magnetic storage systems.

MICROMAGNETIC MODEL

The micromagnetic model approximates the atomistic quantummechanical behaviour of ferromagnetic particles of nano- and micrometer sizes by assuming the magnetization of the material to be a continuous function over space. This holds true in most cases as the interaction between the spins of electrons of neighbouring atoms in a lattice interact strongly and seek to align each other in parallel position (in the case of ferromagnetism, anti-parallel in the case of antiferromagnetism). Thus changes in the magnetization can occur only over a large number of lattice cells. In equilibrium, the local magnetization $\vec{M}$ will align in the direction of the effective magnetic field $\vec{H}_{eff}$, i.e., the torque vanishes

$$\vec{M} \times \vec{H}_{eff} = 0 . \quad (1)$$

Here

$$\vec{H}_{eff} = \vec{H}_{exch} + \vec{H}_{aniso} + \vec{H}_{Zeeman} + \vec{H}_{demag} , \quad (2)$$

where the four terms derive from the exchange energy, anisotropic energy, Zeeman energy, and the de- or selfmagnetization energy, respectively (Aharoni 1996). The details to the individual energy terms have been explained at an earlier conference (Bolte et al. 2004) and are discussed comprehensively in works of Brown (Brown 1963) and Hubert and Schäfer (Hubert and Schäfer 1999), among many others.

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From fundamental thermodynamic considerations, namely, the minimization of a system's magnetic energy and the maximization of entropy, as well as the invariance of the strength of the magnetization the equation of motion for the local magnetization (Landau-Lifshitz-Gilbert-equation) out of its equilibrium can be deduced

$$\frac{d\vec{M}}{dt} = |\gamma|\vec{M}\times\vec{H}_{eff} - \frac{|\gamma|\alpha}{M_S}\vec{M}\times\left(\vec{M}\times\vec{H}_{eff}\right). \quad (3)$$

It describes the change of a magnetization vector over time as a function of the effective magnetic field $\vec{H}_{eff}$ at the location of the vector and some parameters inherent in a magnetic system, i.e., the saturation magnetization M_S, the gyromagnetic constant γ and the damping constant α (Landau and Lifshitz 1935; Gilbert 1955; Brown 1963).

THEORY OF SPIN-WAVES

The magnetization precesses around the direction of the effective field, and its precession frequency depends on the strength of the field. A strong external (Zeeman) field in z-direction will cause a precession in the xy-plane (here assuming small damping and neglecting the anisotropy and exchange terms)

$$\frac{dM_x}{dt} = |\gamma|\left[H_{Zee} + \left(N_y - N_z\right)M\right]M_y \quad (4)$$

$$\frac{dM_y}{dt} = |\gamma|\left[H_{Zee} + \left(N_x - N_z\right)M\right]M_x$$

The *N*s are the demagnetization factors (Newell et al. 1993). A time-dependent solution to this set of differential equations exists if the determinant of the secular equation is zero. The so-called ferromagnetic resonance frequency (Griffiths 1946, Kittel 1958) as a function of the external field strength is then

$$\omega_0^2 = \gamma^2 \begin{bmatrix} H_{Zee} + \left(N_y - N_z\right)\mu_0 M \\ H_{Zee} + \left(N_x - N_z\right)\mu_0 M \end{bmatrix} \quad (5)$$

This relation can be generalized for systems with exchange energy and spatially changing parameters. Then a transition of momentum occurs in the form of moving oscillations in the magnetization, or spin waves. In finite systems, the frequency of spin waves is quantized. Also, if the strength of direction of the effective field is inhomogeneous, eqn. (5) leads to a localization of spin-wave modes.

For structures of certain symmetry, such as spheres, cubes, rings, infinitely long stripes, etc. the spin-wave eigenmodes can be derived analytically (Buess et al. 2005, Bayer et al. 2005; Kalinikos and Slavin 1986). For more complex or irregular structures, the spin-wave eigenmodes and their spatial distribution have to be computed numerically as shown in the next paragraphs.

COMPUTATIONS OF SPIN-WAVE SPECTRA

A standard micromagnetic simulation tool (`OOMMF`, Donahue and McMichael 1999) was enhanced by a faster numerical integration algorithm as explained in an earlier publication (Bolte et al 2005). Also, a tool dubbed SpinWaveAnalyzer, was implemented in MATLAB™ to compute the spin wave spectra for micromagnetic problems. MATLAB was selected because it allows quick implementation of functioning code and its large libraries of solutions to standard problems of many aspects related to this topic, from linear algebra to signal processing, plotting functions, etc. Release 14 also allows for a rapid input of binary and text data, which was important to create a fast interface between the simulation tool and the SpinWaveAnalyzer.

With the simulation tool the time evolution of the magnetization was computed by step wise integration of the Landau-Lifshitz-Gilbert equation. For the simulation, Permalloy parameters were used, i.e., an exchange constant of A= 1.3×10^{-11} J/m, a saturation magnetization of $M_s = 8 \times 10^5$ A/m, a uniaxial anisotropy K_1 = 100 J/m³, and a damping constant of α=0.008. The initial states were determined for every problem separately. The simulation was thus as to excite the magnetization by out- of-plane field pulses with full-widths-at-half-maximum (FWHM) of 2.5 ps and a peak amplitude of 20 mT and exponentially rising and falling edges to account for a gradual change in the simulation's time step. This was done so that the frequency response of the excitation is virtually constant between zero and well over 100 GHz, the range in which resonance modes are to be expected. The pulses lengths and heights were chosen small enough to ensure that all spin-wave modes are in the linear regime. The external field pulses are simulated to be in the out-of-plane direction to prevent unwanted domain wall or vortex motion.

The problem was then simulated and the magnetization response to the excitation recorded for simulation times *T* between 20 ns and 45 ns, long enough to achieve the frequency resolution $\Delta f = 1/T$ necessary to resolve adjacent modes in the spectra. The storage intervals were so that the Nyquist frequency f_{Ny} = ½ f_{Sam} was above the highest resolvable eigenmodes. This meant a sampling frequency of ca. 50 GHz. The stored data for the magnetization $\vec{M}(t_i)$ for times $t = i\cdot\Delta t$, $i \in \{1,...,n\}$ was read into matrix format to allow for MATLAB's matrix formalism to be used. The magnetization was then locally Fourier transformed for every simulation cell. Then the local power density, i.e., the squared amplitude for every pixel was integrated over the whole geometry to yield the global power density. Also, the local power densities were mapped for each frequency to show the inhomogeneous distribution of the power density for the corresponding frequency. The same was done for the phases, so that the complete information of the magnetization oscillation was

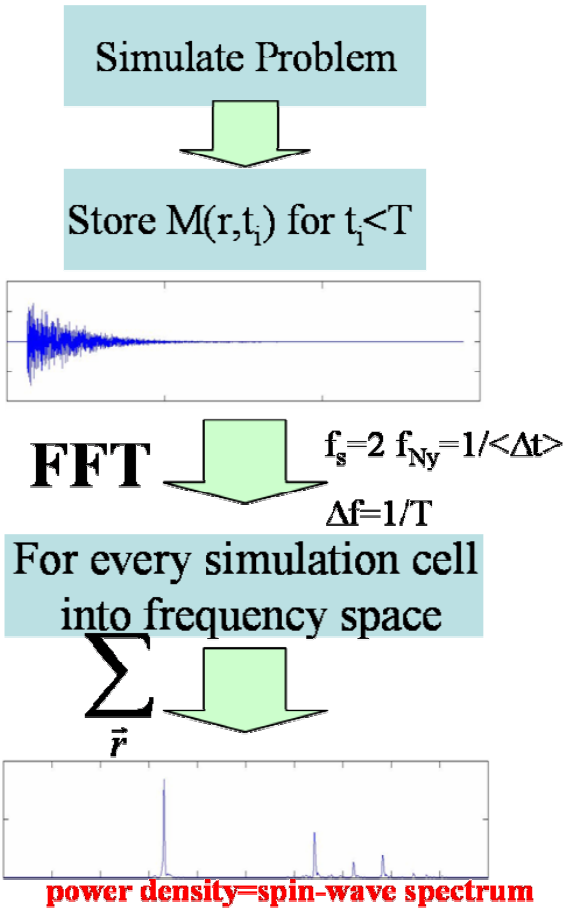

Figure 1: Flow chart of the SpinWaveAnalyzer. First the temporal evolution of the magnetization is derived by solving the Landau-Lifshitz-Gilbert-equation numerically via an enhanced micromagnetic simulation tool and the data is stored for N time steps. Then the data is Fourier-transformed for every pixel separately. Finally, the squared amplitude is integrated for all pixels for every frequency step so that even eigenmodes do not cancel out (see Fig. 2). Intensity images for the squared amplitude are plotted (see Fig. 3). The same procedure is followed for the phases.

preserved by the Fourier transformation. A flow chart of the SpinWaveAnalyzer is shown in Fig. 1.

RESULTS

As a first test case, small squares of lateral sizes between 750 nm and 4 µm and a thickness of 16 nm (lateral cell sizes 5 nm except for the 4 µm square where it was 10 nm) were simulated to compute the eigenmodes of such systems when exciting them with field pulses of different spatial symmetry. Squares are interesting because they contain all fundamental static magnetization configurations, i.e., vortices, domain walls, and domains. This was done to verify and understand experimental results by notable research groups that have shown some eigenmodes but differ in details (Park et al 2002; Perzlmaier et al. 2005; Quitmann et al. 2005). Our claim is that even small spatial asymmetries in the exciting field pulses can evoke different mode patterns and that properly chosen spatial symmetries of the pulses give access to the rich set of eigenmodes in ferromagnetic micro- and nanostructures. The pulse was spatially modulated to locally invert its direction and thus to allow the excitation of spin-wave eigenmodes of distinct symmetries. By using spatially inhomogeneous field pulses, we excite different modes and show that they reflect the symmetry of the exciting torque. For simplification, the discussion of the eigenmodes was restricted to modes with their main power within the four domains. Some results were published recently (Bolte et al. 2006a), while others are in the process of publication (Bolte et al. 2006b). Exemplary results are shown in Fig. 2. The increase in power at certain frequencies of over 15 dB as well as their small full width at half maximum is clearly seen in all graphs (a) to (d). In Fig. 2(a) is shown the spin-wave spectrum (frequency response) of a relaxation from an artificial initial state in which the out-of-plane components of the magnetization vectors were set to zero. Figure 2(b) shows an excitation with a π/2 rotational symmetric field pulse as shown in the inset. The same frequencies are excited even though the peaks are wider and not as high as in (a). Also, additional, smaller peaks are visible. In Fig. (c) and (d), the same structure was excited, but with π-rotationally symmetric and uniform field pulses, respectively. It is obvious that all three excitations create completely different spin-wave modes. A deeper understanding is gained by looking at the local power distribution of the peaks of the different excitations. Figure 3 shows exemplary plots.

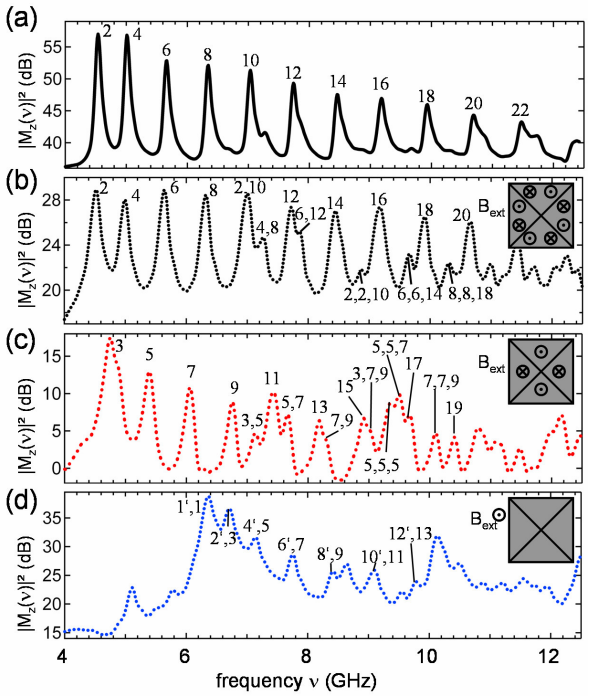

Figure 2: Simulated and computed spin-wave spectra of a 16nm thick, 1x1 µm² large Permalloy square for four different excitations. (a) relaxation of the magnetization from an artificial initial state, (b) –(d) excitation with a 20 mT strong 2.5 ps short magnetic field pulses with the local direction of the pulses as shown in the upper right insets (From Bolte et al. 2006a).

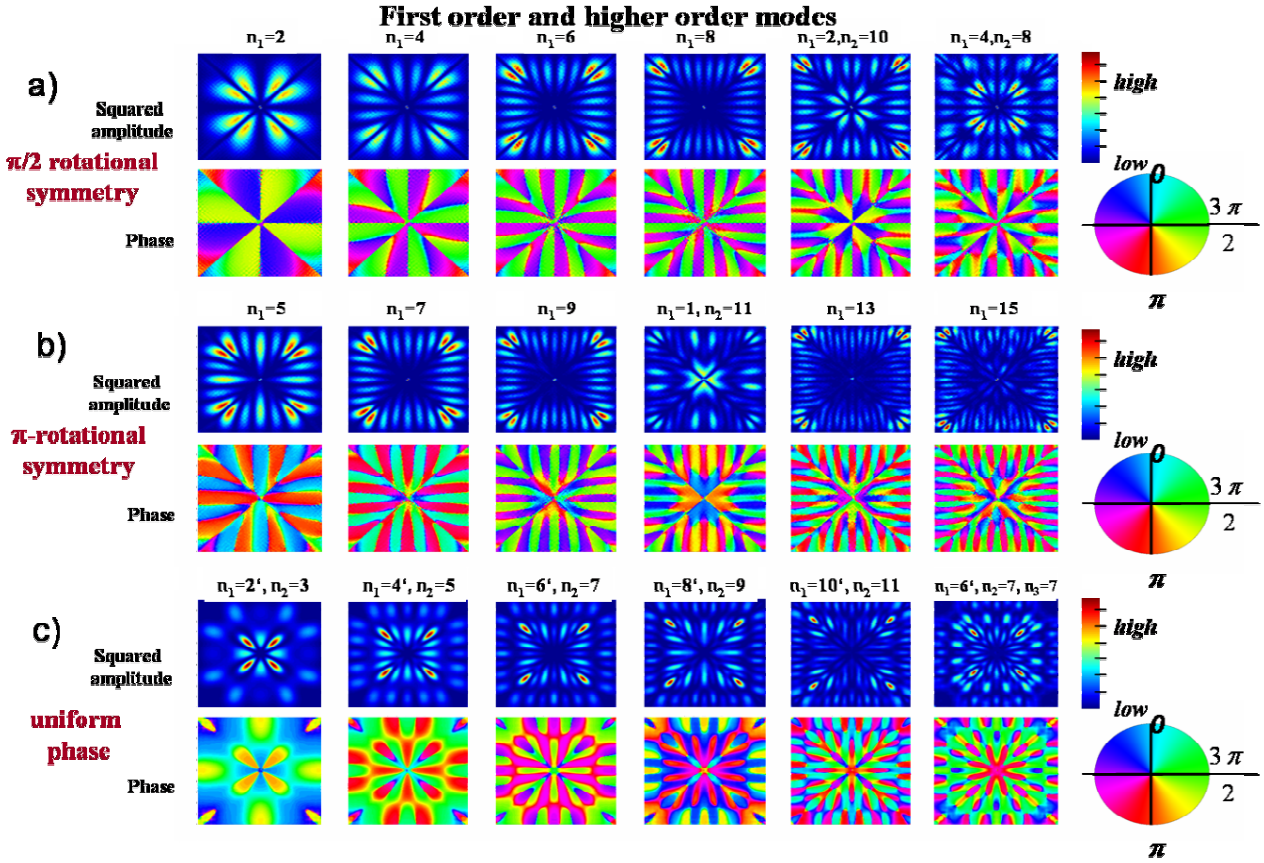

Figure 3: Spatial power density distribution of a 1x1 µm² large, 16 nm thick Permalloy square excited with an out-of-plane field pulse of 20 mT strength and various spatial symmetries, corresponding to the excitations of Figs. 2(b)-(d). Top images represent the local power density, bottom images the phases with the colour coding as explained on the right of each line. (a) Excitation with a π/2-rotationally symmetric pulse as shown in the inset of Fig. 2(b). Only even numbers of maxima exist in each domain. (b) Excitation with a π-rotationally symmetric pulse as shown in the inset of Fig. 2(c). Only odd modes exist. (c) Excitation with a spatially uniform pulse as shown in the inset of Fig. 2(d). Unlike in Fig. 3(a)-(b), the modes exist also within the domain walls, and higher modes perpendicular to the direction of the static magnetization are visible. (From Bolte et al. 2006b).

It is obvious that an even number of modes along the magnetization of a domain are excited by π/2-rotationally symmetric pulses and an odd number of modes are excited by π-rotationally symmetric pulses. This is because with π/2-rotationally symmetric pulses, there is an uncompensated net torque acting on the magnetization of each domain. That means that the oscillations also have a nonzero overall component. The phase images show that neighbouring oscillations are always exactly out-of-phase. It is intriguing that the uniform excitation has a different mode pattern, with their main power density being in the domain walls and not only within the domains. It is not entirely clear why the spin-wave eigenmodes would prefer the domain walls. One possible reason is that due to the lower total energy within the domain walls a potential well is formed that captures the spin waves. It is clear that because of the symmetry of the exciting pulses, the resulting positions of nodal lines prohibit excitation of spin waves in these positions. These findings and other symmetries are discussed in detail in a forthcoming publication (Bolte et al. 2006b).

The insights gained in these simulations were used to study more complex structures such as those likely to be used for magnetic storage systems. In magnetic random access memory (MRAM) cells, a combination of soft magnetic layers and hard magnetic layers with a nonmagnetic spacer layer comprises a so-called magnetic tunnel junction (MTJ). When leading an electric current vertically through such an MTJ trilayer system, the relative orientation of the two magnetic layers will determine the electric resistance of the current. Decreasing the lateral sizes of such cells lead to higher storage densities potentially higher switching speeds, thus testing the cells' sizes for their spin-wave eigenmodes is a suitable problem for the present simulation tool and the SpinWaveAnalyzer.

In Fig. 4 exemplary eigenmode spectra of MTJ trilayers as well as their main modes are shown. For small cells (around 64 nm, see Fig. 4(a)), there are only two major modes, while for larger cells (Fig. 4(c)), there exists a multitude of different peaks corresponding to higher harmonics of two basic modes, the dipolar driven edge mode and the exchange driven centre or uniform precession mode (Stiles and McMichael 2005). The higher harmonics agree well with the theoretical model for infinite thin films that was also used

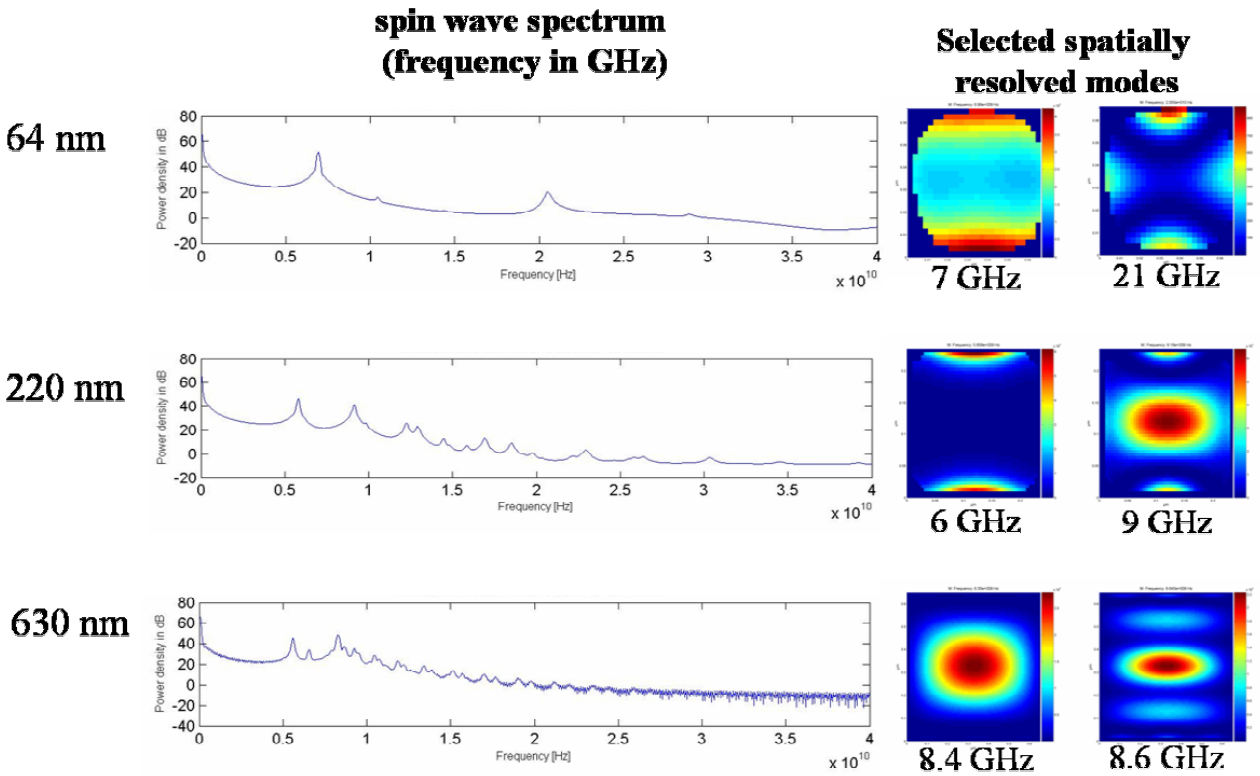

Figure 4: Spin-wave spectra of magnetic multilayers for magnetic data storage of different lateral sizes. Shown are the frequency response (centre) and the local power density of two major spin-wave eigenmodes (right) for three exemplary sizes. Top: 64 nm small storage cell. Only two modes. Middle: 220 nm cell. Several modes exist. Bottom: 630 nm cell. Many modes, two basic modes with higher harmonics can be seen in the spectrum.

to describe the eigenmodes in the Permalloy squares of (Bolte et al. 2006a). This seems quite astonishing, as 630nm large structures can hardly be called infinitely large films. But because the exchange length, the range in which the exchange interaction dominates the magnetic behaviour is only a few nanometres long, the dynamic dipolar interaction of spin-wave oscillations dominates, and regions that oscillate out of phase to each other reduce the total energy of the system. For sizes between 64 nm and 630 nm, there is a crossover between dipolar dominated and exchange dominated mode excitation (Kruglyak et al. 2005).

CONCLUSIONS

We have enhanced a standard micromagnetic simulation tool and have developed a package for the computation of the spin-wave spectra for arbitrary excitation patterns. With the tool and the package, we can determine the magnetic eigenmodes of nano- and microstructured ferromagnets for magnetic storage elements. We find for example that the spin-wave eigenmodes sensitively depend on the spatial symmetry of their excitations and that for decreasing lateral extensions, the oscillatory behaviour of nanosized multilayers shifts from standing spin waves with higher harmonics along and perpendicular to the static magnetization to dipolar modes with higher harmonics situated on the edge of a structure. These simulations can help to find the optimal frequency with which to switch the magnetization of real-life magnetic storage cells, thus enabling the creation of faster, non-volatile, low-power storage concepts that could revolutionize computer architectures.

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