Interpretation of spin-wave modes in Co/Ag nanodot arrays probed by broadband ferromagnetic resonance

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Ferromagnetic resonance (FMR) and the measurement of magnetization dynamics in general have become sophisticated tools for the study of magnetic systems at the nanoscale. In this work, we present a detailed investigation of Co/Ag nanodots with a 200 nm diameter arranged in a square pitch array with a periodicity of 400 nm, which, due to their size, can support standing spin-wave modes with complex spectral responses. To interpret the experimentally measured broadband FMR, we compare the spectra of the nanoarray structure with those of the unpatterned Co/Ag film of identical thickness, which serves as a baseline for obtaining the general magnetic parameters of the system. Using state-of-the-art simulations of the dynamic response to identify the nature of the excitation modes allows us to assess the boundary conditions for the nanodots. We then proceed to calculate the spectral response of our system, for which we obtained good agreement. A full description of the theoretical framework and its application to our system is provided and the novel frequency domain, matrix-free simulation method used is described in detail.

Index Terms—Ferromagnetic resonance, magnetization dynamics, micromagnetism, nanostructures, spin waves

The study of the magnetic properties of nanostructured arrays is a key area of research in modern magnetics and a central field in nanomagnetism. These systems display a number of properties, which are modified due to the spatial confinement of the magnetic layer as well as surface anisotropy effects. This confinement includes both the vertical thickness and the lateral dimension of the patterned structures such as, e.g., nanodots.

Ferromagnetic resonance (FMR) provides a versatile and sensitive probe of the magnetic state of low dimensional systems, such as nanostructured arrays, and is an ideal tool to study the magnetization dynamics. Of particular importance is its sensitivity to the magnetic boundary conditions that determine the allowed wave vectors in standing spin-wave (SSW) modes. These are responsible for the modal patterns and, hence, the $f(H)$ characteristics of the magnetic system. In this work, we describe a detailed experimental-theoretical study of Co/Ag nanodot arrays of size 0.5 mm × 0.5 mm with an individual dot diameter of about 200 nm and a pitch of 400 nm, which have weak interactions due to their spatial separation.

Magnetization dynamics of the samples have been investigated by means of broadband vector network analyzer FMR at room temperature and at frequencies up to 40 GHz [1]. As an example, the in-plane easy axis $f(H)$ dependence of a single Co/Ag nanodot array is depicted in Fig. 1(a). We note that there are two dominant modes with roughly the same intensity and which appear to be modified with respect to the resonances observed in the continuous Co/Ag film. In addition to these modes, there is a further resonance line of weaker intensity on the high-field (low-frequency) side of the main resonances.

To evaluate the nanodot spectra, we first fit the experimental data of the film sample to the corresponding resonance equations, from which we derive the relevant material constants and pinning conditions. For this, we provide a detailed outline of the theoretical framework necessary for a correct understanding of the resonance absorption phenomena observed. Next, we have to consider the effect of nanopatterning and need to account for mode numbers in three dimensions. However, the complexity of the analysis means that we require some further input into identifying the possible excitation modes responsible for the observed resonance peaks.

To assist this process, we have used micromagnetic simulations of the nanodot structure based on a recently-developed frequency-domain micromagnetic approach [2].
For a full discussion of the simulations, see Appendix A in [1]. As an example, we illustrate in Fig. 1(b) the simulated power spectrum of a Co/Ag nanodot array for an in-plane applied field $\mu_0 H = 0.3$ T. For the three principal modes, at frequencies of 9.4 GHz, 13.6 GHz, and 16.3 GHz, the corresponding modal patterns are illustrated in the inset of Fig. 1(b). The most intense mode (III) in this simulated spectrum is observed at 16.3 GHz. It is the fundamental mode for the specific boundary condition of the nanodots, where spin precession concentrates mostly in the center of the nanodots. The resonances (I) and (II) at 9.4 GHz and 13.6 GHz, respectively, have modal patterns indicating an edge-localized character, meaning the excitations are concentrated at the edge of the nanodot, whereas the center of the dots shows no spin precession. The degree of localization is related to the mode profile and the extent of the spin precession towards the interior of the magnetic body. Due to the localized nature of the excitation, these modes will have frequencies below the theoretical uniform mode and excitations fields above the uniform resonance field. As such, the mode with 9.4 GHz is further away from the uniform mode than the resonance with 13.6 GHz.

From the expected spin-wave spectrum, see Appendix C in [1], we evaluate the frequencies of the lowest lying SSW modes (since these will be closest to the fundamental mode and in the range of measured values), which can be calculated from [1]

$$f_{pqr}^2 = f_{\text{FMR}}^2 + \frac{(\mu_0 \gamma)^2}{4\pi^2} [Dk_{pqr}^2 (2H + M_s) + (Dk_{pqr}^2)^2]. \quad (1)$$

We find an excellent agreement between the calculated and experimental values for the frequencies of the fundamental (uniform-like) mode (001) at around 17.5 GHz. The existence of an edge-localized mode in the experiment has been confirmed and fits very well with theory and micromagnetic simulations, having the form of a flapping mode at the extrema of the nanodot in one of the in-plane directions. Its frequency is below the fundamental mode’s frequency and has been shown to be a consequence of the imaginary wave vector for such localized SSW modes.

Higher order SSW modes can be generated from the theory, which allows us to find a probable mode number for the second bulk SSW (201 or 131) that lies at frequencies above the fundamental mode. While the assignment of this mode is not entirely unambiguous, both in the framework of the model and in the considerations for the spin-wave modes accessible therein, we provide a satisfactory explanation of all the experimental observations.

Overall, we illustrate a consistent approach to the full interpretation of our experimental measurements, where there is a good degree of confidence and agreement between theory and experiment.

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