SPIN WAVE RESONANCE OF FERROMAGNETIC NANOWIRE ARRAYS

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Spin waves in ferromagnetic materials exhibit a large variety of field-tunable dispersion relations, permitting the manipulation of microwaves in solids. While magnetic oxides, such as ferrites and garnets, have traditionally been used for such purposes [1], an increasing interest has recently been dedicated to magnetic wave propagation in artificially-nanostructured magnetic materials. This emerging research field, called magnonics, seeks to exploit magnetic wave phenomena in order to process information at the nanoscale [2–4].

Here we are concerned with magnonic materials consisting of nanowires, made of ferromagnetic metals electroplated in nanoporous alumina membranes [5–7]. By combining metallic and ferromagnetic nanoinclusions in a dielectric template, one can exploit various charge and spin transport phenomena, along with spin and charge density waves, to achieve magnetic and dielectric responses not found in nature.

EFFECT OF DIPOLAR INTERACTIONS ON FERROMAGNETIC RESONANCE

Ferromagnetic resonance (FMR) generally refers to the collective resonance modes of strongly coupled spins in ferromagnets. Unlike the magnetic resonance of paramagnetic electrons or of nuclear spins, FMR is often shape-dependent and strongly anisotropic. This behavior is due to the strong anisotropic coupling between the elementary magnetic moments in ferromagnets, which results in effective internal fields, related to the crystallographic axes, mechanical stresses or sample shapes [8]. For a specimen with rotational symmetry, magnetized along the symmetry axis, the ferromagnetic resonance frequency (in rad/s) is

$$\omega = \gamma\mu_0\left(H_0 + H_{eff}\right), \tag{1}$$

SUMMARY

We present a brief introduction to the spin wave resonance of ferromagnetic nanowire arrays, emphasizing their relevance for the emerging field of magnonics.

where γ is the gyromagnetic ratio, μ_0 is the vacuum permeability, H_0 is the external applied field and H_{eff} is the effective uniaxial anisotropy field. For soft magnetic materials, dominated by the long-range dipolar interaction between the magnetic moments, the effective field is

$$H_{eff} = \left(\frac{1-3N_z}{2}\right)M_s, \tag{2}$$

where M_s is the saturation magnetization and N_z is the component of the diagonal demagnetizing tensor parallel to the magnetization [6]. Note that $N_x+N_y+N_z=1$, where N_x and N_y are the other two orthogonal components of the diagonal demagnetizing tensor.

Demagnetizing effects, arising from dipolar interactions, lead to shape dependent FMR characteristics, related to the value of N_z in Eq. (2). Figure 1 shows the expected behavior for a longitudinally magnetized CoFeB wire ($N_z=0$), a CoFeB sphere ($N_z=1/3$) and a thin CoFeB film magnetized perpendicular to the plane ($N_z=1$). The offset of the linear FMR characteristic is a measure of the effective anisotropy field, associated with dipolar interactions.

In soft magnetic nanowire arrays, the shape-dependent demagnetization of the individual wires is modified by the inter-wire dipolar interactions. This leads to an effective demagnetizing tensor, which is a function of the geometrical parameters of the array (wire length, diameter and spacing) and of the saturation magnetization of the wires [6]. This is illustrated in Fig. 1, where the resonance field for a film of densely-packed vertical wires (perpendicular to the film surface) magnetized parallel to the wires exhibit an effective demagnetizing tensor somewhere between that of a wire and a thin film.

Over the years, we have verified that, provided there are no other contributions to the magnetic anisotropy, the ferromagnetic resonance characteristics of these arrays can be tailored by adjusting their geometrical parameters during the fabrication process[1]. Interestingly, with proper choice of geometric parameters, an array of ferromagnetic wires

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[1] This has been generally observed in several Ni, NiFe and CoFeB samples, with the exception of the smaller diameter wires (around 20 nm), for which a surface magnetic anisotropy starts to contribute to the FMR response.

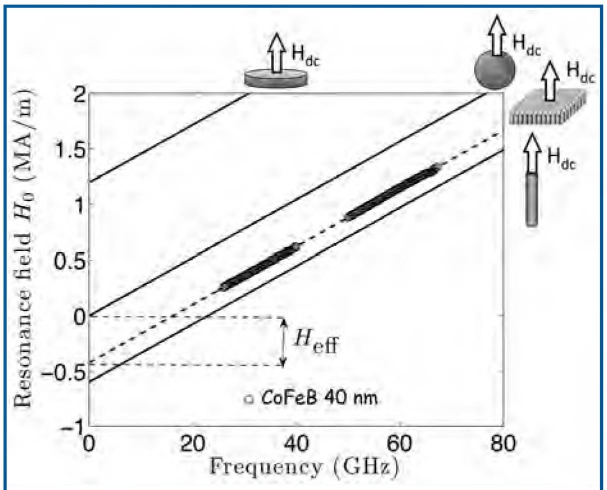

Fig. 1 Ferromagnetic resonance field as a function of frequency, for different sample shapes: wire (axial field), sphere, uniform film (magnetized out-of-plane) and 40-nm-diameter CoFeB nanowire array. The material, an alloy of CoFeB, is characterized by $M_s = 1200$ kA/m and $\gamma = 1.92 \times 10^{11}$ rad/(s.T). The open circles are the measured data of the array. The dashed line is a fit, using Eq. (1) with 0 by $M_s =$ 1200 kA/m and $H_{\text{eff}} = 422$ kA/m, in agreement with the dipolar field calculated from the parameters of the array [6].

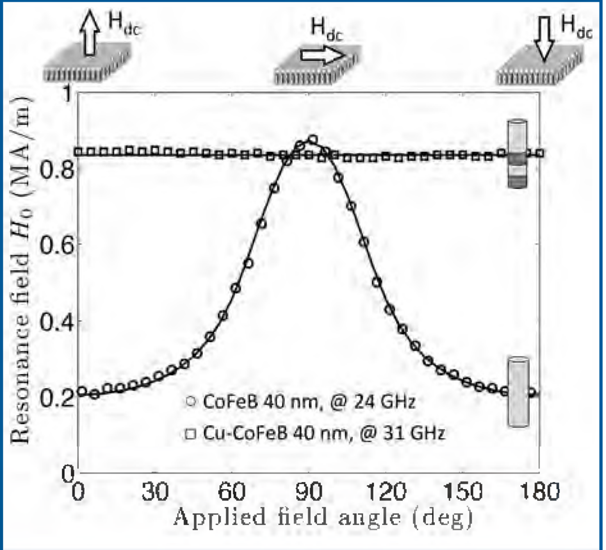

Fig. 2 Angle-dependent resonance field of a 40-nm diameter CoFeB nanowire array (circles) and a 40-nm diameter multilayered Cu-CoFeB nanowire array (squares). The solid lines are fits, using Eq. (29) from Ref. [6], with $H_{\text{eff}} = 422$ kA/m and $\gamma = 1.92 \times 10^{11}$ rad/(s.T) for the uniform array and $H_{\text{eff}} =$ 0 kA/m and $\gamma = 1.86 \times 10^{11}$ rad/(s.T) for the multilayered array.

could be forced to be isotropic, as if it was a sphere! This is demonstrated by the angle-dependent FMR measurements in Fig. 2. In this example, we have used multilayered nanowires, alternating Cu and CoFeB layers, to gain even more flexibility to adjust the effective demagnetizing factor. While the uniform composition wires exhibit the characteristic bell-shaped curve expected from an out-of-plane uniaxial anisotropy, the multilayered nanowire arrays display an FMR field independent of the direction of the applied field.

MAGNONIC MATERIALS

The control over the FMR characteristics of magnetic materials is an important step towards the realization of magnonic devices. Magnonics relies on the propagation of spin waves in man-made periodic structures to transport and process information signals. The relatively short wavelength of the spin waves, on the order of 100 nm in the low-GHz frequency regime, as compared to several cm for EM waves, holds promise for nanoscale devices. While other fields of research, such as plasmonics, also seek to exploit short wavelength excitations in solids, what sets magnonics apart is its larger variety of spin wave dispersions and the fact that these are tunable using an external magnetic field. For example, a magnetic field can be used to modify dynamically the band structure of a magnonic crystal [9]. In this respect, the possibility to reconfigure the remanent magnetic state (no applied field) of ferromagnets, is of great interest for the design of reprogrammable devices, an important theme of magnonic research [Other aspects of spin waves are also covered in the following articles also in this issue: "*Dawn of Cavity Spintronics*" by Hu, "*Instability Processes for Magnons in Ferromagnetic Nanostructures*" by Cottam and Haghshenasfard, "*Electronic transport in magnetic tunnel junction: a discussion of the electron-magnon-photon coupling*" by Guo and Xiao and "*The 'holy grail' of multiferroic physics*" by de Sousa].

Ferromagnetic nanowire (FMNWs) arrays, exhibiting significant hysteresis, are potential candidates for self-biased reprogrammable magnonic devices. If not magnetically saturated, the FMNWs arrays can be modelled by considering the systems as two magnetically-uniform antiparallel arrays, strongly coupled by dipolar interactions [10,11]. In other words, each nanowire has a uniform magnetization, which points either up or down, thus creating two embedded sub-arrays. The distribution between up and down wires can be adjusted using minor hysteresis cycles. It is worth mentioning that this feature would be very difficult to achieve, if not impossible, in conventional ferrites and garnets.

Figure 3 presents the frequency dependence of the effective complex permeability of a FMNWs array, measured at four different applied fields. The four fields correspond to four distinct magnetic states along the lower branch of the hysteresis curve. As the field is swept from −5 kOe to 5 kOe (1 kOe = 79.6 kA/m), the nanowires randomly reverse, gradually modifying the resulting dipolar fields. The component of the scalar effective permeability, presented in Fig. 3c, are associated with

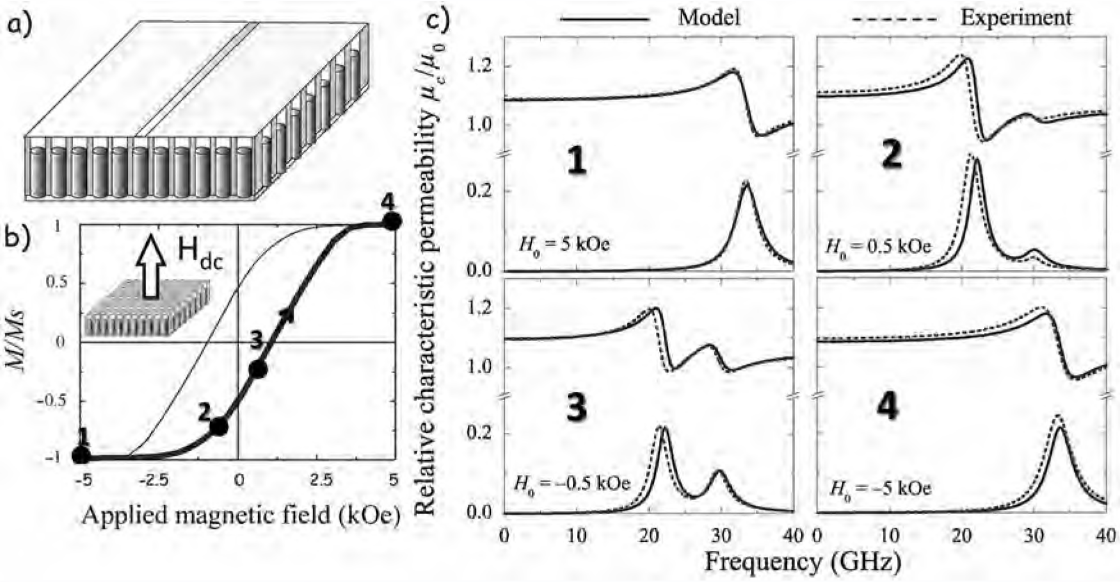

Fig. 3 a) Illustration of the measured device consisting of a CoFeB FMNWs array built into a microwave transmission line, b) Hysteresis loop of a 40-nm diameter CoFeB nanowire array, c) Real and imaginary parts of the effective permeability at several points along the lower part of the major hysteresis curve. Dashed lines are experimental data. Solid lines are theoretical calculations [10]. (Note: 1 kOe = 79.6 kA/m)

the microwave magnetic field, which is perpendicular to the static applied field, H_0. It is complex due to magnetic damping, and exhibits the characteristic dissipation (imaginary part) and dispersion (real part) of a resonant response. The solid line is the calculated response, based on the simple dipolar model, presented earlier, but applied to the two sub-arrays and including the mutual coupling between the arrays [10].

At saturating fields (points 1 and 4), all magnetic moments are oriented in the same direction, corresponding to a single resonance. At lower field (points 2 and 3), two resonance peaks are observed, associated with the normal modes of the coupled sub-arrays, as detailed in Ref. [10]. As indicated by the relatively good agreement between the data (dotted line) and the model (solid line), the response is generally well described using two coupled magnetic oscillators, with resonance characteristics depending on the relative distribution of the wires between the parallel and antiparallel directions.

CLOSING REMARKS

In this brief introduction to one aspect of magnonics research, we have shown that the microwave response of ferromagnetic nanowire arrays can be surprisingly well accounted for by a simple model, assuming a periodic array of single-domain cylindrical ferromagnets, exhibiting bistable hysteresis, and mutually coupled by dipolar interaction. The model leads to quantitative expressions for the effective anisotropy field as a function of the material and geometrical parameters of the arrays [6], which can be used as design rules to engineer their properties. However, this increased design flexibility is provided at the cost of higher microwave losses, as compared to state-of-the-art ferrites and garnets. Microwave losses originate from the damping of the precessing magnetization and are related to the linewidth of the imaginary part of the effective permeability. Understanding and reducing the microwave losses, along with demonstrating spin wave propagation in FMNWs-based magnonic waveguides is an active research field in our group.

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