X-ray ferromagnetic resonance spectroscopy

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We present a method to measure continuous-wave ferromagnetic resonance (FMR) spectra based on the core-level absorption of circularly polarized x rays. The technique is demonstrated by using a monochromatic x-ray beam incident on a yttrium–iron–garnet sample excited by a microwave field at 2.47 GHz. FMR spectra are obtained by monitoring the x-ray absorption intensity at the photon energy corresponding to the maximum of the magnetic circular dichroism effect at the iron L2,3 edges as a function of applied magnetic field. The x-ray FMR signal is shown to be energy dependent, which makes the technique element sensitive and opens up new possibilities to perform element-resolved FMR in magnetic alloys and multilayers. © 2005 American Institute of Physics. [DOI: 10.1063/1.2089180]

Techniques based on ferromagnetic resonance (FMR) are widely employed for the analysis of magnetic materials and thin films.1,2 Recent developments have seen the implementation of FMR detection schemes alternative to conventional inductive methods, such as those based on magnetic resonance force microscopy3,4 and Kerr effect.5,6 Behind these efforts is the need to understand and optimize the dynamic response of magnetic compounds and devices of increasing complexity.7 In this context, the development of methods capable of elemental analysis represents an obvious advantage, allowing one to investigate crucial issues such as the dynamic coupling and magnetization relaxation of elemental moments in alloys,8–10 molecular compounds, exchange-coupled multilayers,1,2,11,12 as well as current-induced magnetization excitations in spin-valve structures.13,14 Very promising results in this direction have been obtained in the time domain by pump-probe x-ray magnetic circular dichroism (XMCD) experiments with sub-ns resolution, taking advantage of the element-resolving power of core-level x-ray absorption.15–17 Recently, Bailey et al.18 have shown that time-resolved XMCD allows to detect the precessional frequency of elemental magnetic moments in a ferromagnetic alloy. Here, we propose and demonstrate a method to measure continuous-wave FMR spectra by means of XMCD by studying the time-averaged x-ray absorption signal of Fe in YIG (Y3Fe5O12) excited by a microwave magnetic field at GHz frequencies.

XMCD is defined as the dependence of the x-ray absorption coefficient on the relative orientation of the photon helicity \( \sigma \) with respect to the sample magnetization \( \mathbf{M} \).18 The XMCD effect scales as the scalar product \( |\sigma \cdot \mathbf{M}| \). The proposed technique exploits this dependence to detect time-averaged variations of the x-ray absorption signal due to the resonant excitation of precession modes that affect the projection of \( \mathbf{M} \) onto its equilibrium direction, which is set parallel to \( \sigma \) by an external field \( \mathbf{B}_0 \). The experimental setup, schematically shown in Fig. 1, consists of a coplanar waveguide \( \lambda/2 \) resonator placed in a static magnetic field \( \mathbf{B}_0 \) that can be swept between 0 and ±0.5 T. A YIG polycrystalline slab was chosen as test sample, owing to its intense FMR response. The sample, with dimensions \( 1 \times 1 \times 0.05 \text{ mm}^3 \), was positioned at the center of the resonator. At its resonance frequency \( \omega=2\pi\times2.47 \text{ GHz} \), the resonator produced a microwave magnetic field \( \mathbf{B}_1 \approx 0.1 \text{ mT} \) parallel to the sample surface with an input power of 100 mW. The amplitude of \( \mathbf{B}_1 \) close to the resonant field, however, is not precisely known due to the feedback of the sample susceptibility on the resonator tuning. The experiment was carried out at Beamline ID08 of the European Synchrotron Radiation Facility in Grenoble by using the photon beam generated by two helical undulators with nearly 100% circular polarization rate. The intensity of the x-ray beam was \( 2 \times 10^{13} \) photons/s with an energy resolution of 1.2 eV at 700 eV, and a spot size of 0.2 \( \times \) 1 mm\(^2\) at the sample position. The beam incidence direction was aligned with \( \mathbf{B}_0 \) and set perpendicular to the sample surface. X-ray absorption spectra (XAS) were measured by recording the sample fluorescence yield by means of a Si photodiode (Eurysys-Canberra, France) as a function of the incident photon energy. X-ray FMR (XFMR) spectra were recorded at a fixed photon energy as a function of \( \mathbf{B}_0 \) in

![Schematic representation of the XFMR setup](http://apl.aip.org/apl/graphics/fig1.png)
The XMCD decreases to zero as \( I/H_2 \) solid line and antiparallel (\( \sigma^- \), solid line) to \( B_0 = -0.5 \) T. The dc fluorescence current \( I_{dc} \) is shown normalized to the incident photon flux \( I_0 \), measured by the drain current of the first refocusing mirror upstream of the sample. The XMCD spectrum \( [I_{dc}(\sigma^+) - I_{dc}(\sigma^-)]/I_0 \) is shown at the bottom. The spectra are not corrected for<br>self-absorption effects. (b) \( I_{dc} \) vs. \( |B_0| \) recorded at the \( L_3 \) edge (\( E=709.4 \) eV) and (c) \( L_2 \) edge (\( E=722.8 \) eV).

The key feature of the spectra in Fig. 3 is the reversed sign of the XFMR peak for the \( \sigma^+ B_0^- \) configurations with respect to \( \sigma^- B_0^+ \). This, together with the sign inversion at the \( L_3 \) and \( L_2 \) edge, represents compelling evidence of the XMCD origin and photon energy dependence of the observed signal. By comparing the amplitude of the XFMR peak (~15 pA) with the variation of \( I_{dc} \) in Figs. 2(b) and 2(c) corresponding to the complete reversal of \( M \) (~5 nA), the variation of the \( z \) component of the magnetization \( M_z \), with respect to its static equilibrium value \( M_s \), is estimated to be about 1%. An interesting point is that the negative and positive XFMR peaks do not have the same amplitude. Part of this effect is due to the asymmetry of the XMCD origin and photon energy dependence of the observed signal.

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Fe d-states with different total angular momentum quantum number $J_d$ affect the XAS intensity and XFMR amplitude via the dipolar selection rules in an asymmetric fashion depending on the relative alignment of $\mathbf{a}$ and $\mathbf{B}_1$. Investigating the dependence of the XFMR asymmetry for larger microwave power levels than are presently available in our setup might help to elucidate the physical origin of the asymmetry.

The noise level in the XFMR spectra corresponds to 2 pA/$\sqrt{Hz}$, i.e., one order of magnitude larger than the shot noise limit expected from values of $I_{dc}$ of about 100 nA, typical of our experimental conditions. The additional noise appears to be due to instabilities in the x-ray beam intensity. The signal amplitude was found to increase linearly with applied microwave power ($\propto B_1^2$), as expected for $B_1 < \Delta B_0$. Augmenting $B_1$ represents the most straightforward way to improve the signal-to-noise ratio. Moreover, we found that $I_{dc}$ and $I_{ac}$ increase linearly with the beam intensity whereas the noise level is proportional to $\sqrt{I_{dc}}$. Therefore, the signal-to-noise ratio can be ameliorated also by maximizing the beam intensity and the solid angle covered by the photodiode.

To completely rule out the presence of spurious signals, such as inductive coupling between the photodiode and the resonator or field-modulated noise from stray photoelectrons emitted from the sample, we have performed a series of control experiments as reported in Fig. 4. We observe that: (1) When the x-ray beam is shut off and (2) when the photon energy is chosen in a spectral region where the dichroism is weak, no signal is detected above the noise level; (3) the XFMR signal disappears if $B_1$ is turned off; and (4) the XFMR spectra are similar, but not identical to the FMR spectra simultaneously detected by measuring the microwave power reflected from the resonator by conventional methods. The latter effect is attributed to the difference between surface- and bulk-sensitive measurements due to the x-ray absorption length in this energy range ($\sim 20$ nm).

Given the XAS surface sensitivity, XFMR can be applied to samples with thickness down to a few tens of nm without considerable loss of signal. This makes it straightforward to extend XFMR to metallic samples where the skin-effect limits the penetration of microwave radiation. Future experiments will test the possibility to perform XFMR using the photoelectron yield rather than fluorescence yield detection to further augment the surface sensitivity of the technique. X-ray detection of electron paramagnetic resonance, e.g., on metalorganic compounds, constitutes a possible extension of this technique.

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