Coherent ultrafast magnetization dynamics non-resonantly induced in cobalt by an intense Terahertz transient

F. Ardana-Lamas[1], C. Vicario[1], P.M. Derlet[2], B. Tudu[3], J. Luning[3] and C.P. Hauri[1,4]
[1]*SwissFEL, Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland*
[2]*Paul Scherrer Institute, Condensed Matter Theory Group, 5232 Villigen PSI, Switzerland*
[3]*Université Pierre et Marie Curie, LCPMR, UMR CNRS 7614, 75005 Paris, France*
[4]*Ecole Polytechnique Federale de Lausanne, 1015 Lausanne, Switzerland*
Author e-mail address: christoph.hauri@psi.ch

Abstract: We demonstrate non-resonant magnetization dynamics in the ferromagnetic cobalt thin film induced by a record high-field Terahertz pulse. The magnetization dynamics are coherent and exactly follow the THz carrier oscillations.
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1. Introduction

Since 1996 femtosecond near-IR laser pulses (λ=800 nm) have been used to induce fast de-magnetization in ferromagnetic thin films [1]. In those experiments optical pulses manipulate the magnetization by heating the spin system via ultrafast electronic excitation. The associated cooling dynamics were orders of magnitude slower than the ultrafast demagnetization process and took place over hundreds of picoseconds. The incoherent nature of laser-induced heat in the thin film precluded any possibility of imprinting the phase properties of the stimulus onto the magnetization dynamics. Furthermore the thermionic dynamics are slow and do not allow potentially for precise ultrafast switching of magnetic domain on the femtosecond time-scale.

Here we demonstrate a new class of laser-matter interaction thanks to the advent of non-ionizing, high-field Terahertz (THz) pulses. The unique THz pulses at hand [2] induce non-*resonant* femtosecond magnetization dynamics. These ultrafast magnetization dynamics are phase-locked to the THz carrier and thus follow exactly the ultra-strong, phase-stable laser magnetic THz field. In this new interaction regime the laser's phase and field magnitude characteristics are directly imprinted onto the magnetization response, in absence of any resonant mode. This becomes possible since the off-resonant phase-locking mechanism presented here, injects only minor entropy into the system.

2. Experimental results

For our experiment we used the magnetic component of a high-field single-cycle Terahertz transient with a field strength of 0.4 Tesla (Fig. 1, dotted line). The strong Terahertz transient is generated by optical rectification of a powerful mid-infrared pulse in an organic crystal. Upon illuminating the ferromagnetic sample (cobalt thin film), the Terahertz field induces an ultrafast magnetic response which follows the THz stimulus field almost instantaneously (Fig. 1. red line). The dynamics were measured by recording the magneto-optical Kerr effect (MOKE).

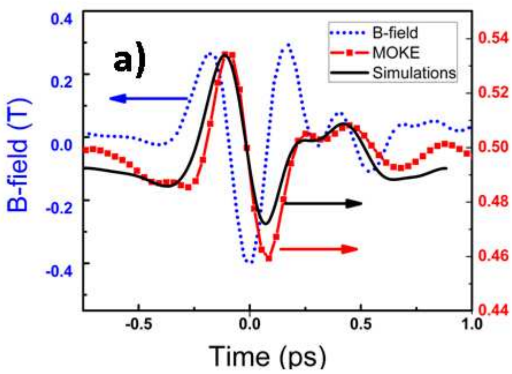

Fig. 1 Magnetization dynamics measured by MOKE (red line) are initiated by the Terahertz magnetic field carrier (dotted line). After the THz pulse left the magnetization dynamics are terminated corroborating the non-thermal excitation of this new interaction scheme [3].

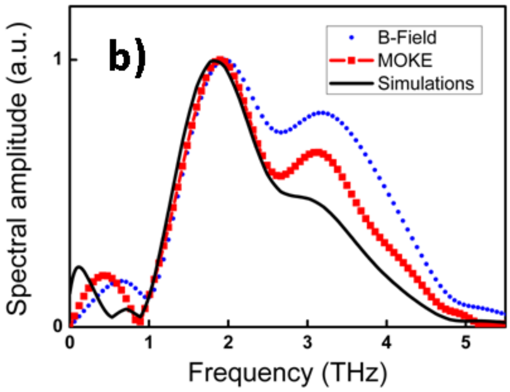

Fig. 2. Spectral intensities of the THz stimulus (dashed line) and the corresponding magnetic response in the Co thin film (red line). The calculated magnetization dynamics are excellently described by Landau-Lifshitz-Gilbert equation both in the temporal and spectral domain.

Shown in Figure 2 is the spectrum of the THz and the measured magnetic response represented by the MOKE frequency spectrum (red). It manifests the occurrence of THz constituents with the same frequencies as observed for the THz stimulus spectrum (dashed blue line). This is the first evidence that ultrastrong Terahertz radiation is capable to initiate non-resonant magnetization dynamics. The experimental results are excellently reproduced by the Landau-Lifschitz-Gilbert (LLG) formalism in which the magentization evolution is described by

$$d\vec{M}/dt = -\gamma\left(\vec{M}\times\vec{B}\right) - \gamma\alpha\left(\vec{M}\times\left(\vec{M}\times\vec{B}\right)\right)/\left|\vec{M}\right|.$$

As corroborated by LLG the observed out-of-plane magnetic response is entirely determined by the precessional term and the THz field contribution. The observed inherently phase-locked interaction between the THz stimulus and magnetization occurs on a femtosecond timescale which has not been expected to be that fast. The experiment gives for the first time evidence that the LLG equation is not only valid for DC magnetic fields but also for rapidly oscillating stimulus on the femtosecond time-scale.

In conclusion we demonstrate that the advent of THz field transient of >0.4 Tesla opens a new class of laser-matter interaction. Previously inaccessible sub-cycle magnetization dynamics are visualized in a ferromagnetic thin film thanks to the non-ionizing THz field. The measured coherent magnetization response is phase-locked to the stimulus and occurs on a femtosecond timescale. The key tool is the intense single-cycle Terahertz pulses recently developed by our group. The opto-magnetic interaction is remarkably well described by the phenomenological LLG approach which is usually valid only for DC field. The presented new concept of phase-stable non-ionizing high field stimulus opens the door to light-induced phase-locked magnetization control towards ultrafast switching of magnetic domains.

3. References

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