Metropolis Monte Carlo analysis of all-optical switching

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ABSTRACT

This paper deals with Metropolis Monte Carlo analysis of the all-optical switching. The laser-induced magnetization dynamics with various laser pulse fluencies and durations are followed by analysis of probable transitions occurred in the sample. The calibration of Monte Carlo steps with physical time was performed by comparison with a reference dynamics described by Landau–Lifshitz–Bloch equation. For an accurate description it was necessary to consider a four-temperature model by analyzing the dynamics of electrons, spins, lattice and environment temperatures. All-optical switching conditions were synthesized in a phase diagram that outlines switching and non-switching regions as well as an unpredictable switching region.

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1. Introduction

The description of all-optical switching revealed in the case of ferrimagnetic rare-earth transition-metal alloys [1–4] represents at least a double challenge: primarily by description of the phenomena involved in this process and secondly by technological perspective through possibility of obtaining ultrafast switching. The new way to control magnetization of a material without any external magnetic field but using only a circularly polarized light has the huge potential implication on magnetic data storage, mainly due to the under-picosecond writing speed, incomparable to the one obtained through a regular magnetic field [5–7]. Also, the understanding of photon–electron–lattice interaction mechanism [8–13] present in all-optical switching can create pre-requisites for the development of quantum operations useful in quantum computing besides ultrafast accessing memory devices [14–16].

Alongside with the analysis of switching processes, an important and useful role is given by the ultrafast demagnetization processes [17], because these are inherent effects of directly or indirectly photon actions. After all, the information can be stored in different magnetization states (not necessarily in opposite states), and from this perspective the demagnetization processes can be as useful as the switching processes, because they are obviously interrelated [18,19].

Since the electron spin transitions related to all-optical switching are collective, being based on competition between exchange “glue” interactions and photons–electrons interactions which are quantum specific in both cases (somehow compatible with a statistical approach), the all-optical switching processes can be described through Metropolis Monte Carlo methods. However, the main impediments for such description are given by the pronounced dynamics reflected in the dynamics of temperatures which involve non equilibrium states and by the difficulty of correlating the physical time and Monte Carlo steps [5]. These obstacles can be removed by an accurate management of the temperatures associated to the system elements (by inclusion of spins temperature) and by the calibration of Monte Carlo steps through another model, Landau–Lifshitz–Bloch [20–22] for instance. Once calibrated, the Metropolis Monte Carlo model should adequately describe the dynamics of the system. This approach has been used in this analysis.

In the next sections the general characteristics all-optical switching adapted for Metropolis Monte Carlo analysis are presented. The evolution of the temperatures involved in the process and the results of the analysis of magnetization reversal processes performed in an appropriate virtual sample are summarized in a relevant phase diagram.

2. All-optical switching characteristics

The switching of the magnetic moments by circularly polarized laser pulse is based on the orientation of magnetic moments (spins)
where the first term is the exchange interaction energy [25,26], the second one is the anisotropy energy assumed to be uniaxial with $a \in [1, 2]$ [27] and the third term is Zeeman energy. The effective magnetic field ($\mathbf{H}_{\text{eff}}$) from Zeeman energy component consists in all the actions (which are not present directly in the Hamiltonian expression) exerted on elementary magnetic moments which can be converted into effective magnetic fields

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{eff}} + \mathbf{H}_{m} + \mathbf{H}_{s} + \mathbf{H}$$

(6)

where $\mathbf{H}_{\text{eff}}$ is the effective magneto-optical effective field (3), $\mathbf{H}_{m}$ is the magnetostatic field, $\mathbf{H}_{s}$ is the magnetic component of the wave and $\mathbf{H}$ is the applied field (if any).

As it is typical for Metropolis Monte Carlo methods [28,29], the thermal actions are taken into account statistically through the transition probability associated with transformations allowed in system at the microscopic level

$$P = \min \left(1, \exp \left(-\frac{\mathcal{H}}{k_{B}T}\right)\right)$$

(7)

in which $\Delta \mathcal{H}$ is the energy barrier which must be overcome by the particle which makes the assumed transition, in this case by changing the orientation of the magnetic moments (spins). The correlation between Monte Carlo Steps (MCS) and physical time was performed through Landau–Lifshitz–Bloch model [20,22,30] by starting from the same saturation state and by applying a high magnetic field opposite to the initial magnetization where it was followed whether in both cases the system magnetization and temperature have the same dynamics. The calibration method is a generalization of known approaches [31,32] to the case in which both temperature and effective magnetic field are ultrafast changed. Essential for an accurate description of the system through Monte Carlo method is to have a detailed management of the temperatures involved in switching processes, in this respect a 4-temperature model that provides appropriate descriptions of the temperature-dependent parameters involved in all-optical switching processes. Also, given the fact the system has a large-scale dynamics, from femtoseconds to nanoseconds, in the calibration process has been established the time functional dependence of MCS, through which, in our simulations, the deviation of the magnetization and temperature dynamics to be minimal compared to Landau–Lifshitz–Bloch dynamics for magnetic reversal process considered as calibration reference dynamics.

3. Temperature characteristics

So far, the generally accepted explanation of the dynamics of ultrafast magnetization processes is based on spin specific changes which take place at the quantum level between involved particles (photons and electrons). From this perspective, for a relevant description, in this analysis a 4-temperature model was considered which is an extension of the usual 3-temperature model [17,33] by taking into account the medium constant temperature $T_{m}$ alongside with electron temperature ($T_{e}$), spin system temperature ($T_{s}$), and lattice temperature ($T_{l}$)

$$\begin{align*}
\frac{dT_{e}}{dt} &= \frac{T_{e} - T_{s}}{\tau_{te}} + \frac{T_{s} - T_{e}}{\tau_{es}} + \frac{P(t)}{C_{e}} \\
\frac{dT_{s}}{dt} &= \frac{T_{s} - T_{m}}{\tau_{ts}} + \frac{T_{e} - T_{s}}{\tau_{es}} \\
\frac{dT_{l}}{dt} &= \frac{T_{l} - T_{m}}{\tau_{tl}} + \frac{T_{e} - T_{l}}{\tau_{el}} + \frac{T_{m} - T_{l}}{\tau_{ml}} \\
\frac{dT_{m}}{dt} &= 0
\end{align*}$$

(8)

where $\tau_{xx}$ and $\gamma_{x}$ are specific thermal relaxation times ($x, y = [e, s, l] \equiv \{\text{electron, spin, lattice}\}$), $C_{x}$ is the $x$ specific heat, $\gamma_{x}$ is the thermal $x'–x'$ interaction constant and $P(t)$ is the laser
Fig. 2. The time evolution of electronic ($T_e$), spin ($T_s$) and lattice ($T_l$) temperatures of the sample exposed to a laser pulse with different duration ($\tau_I$) and intensities ($I$).

fluency. In this analysis it was assumed that the local environment temperature does not change under the action of laser beam ($T_m = \text{const}$).

For relevant comparisons, laser pulse intensities ($I$) and durations ($\tau_I$) were represented in relation with the optimal values ($\tau_I^{(0)}$,$I_0$) obtained with Landau–Lifshitz–Bloch model for the same virtual system in which electrical amplitude modulation coefficient is $n = 1$ [20]. The relevant evolution of the temperatures in the sample exposed to a laser pulse with different duration and intensities are shown in Fig. 2.

The four cases of electron–spin–lattice temperature dynamics describe the essential distinct cases, reflecting the effects of duration ($\tau_I$) or intensity ($I$). Thus, for the same laser pulse duration ($\tau_I$) and with increasing of laser beam intensity (see Fig. 2(b) comparative with Fig. 2(a)), spin temperature ($T_s$) may reach or exceed Curie temperature ($T_C$) and the ordered spins system become thermally disordered. The analysis of temperature dynamics for different durations ($\tau_I$) and intensities ($I$), as it can be seen in Fig. 2, revealed that the laser pulse duration and intensity produce similar peak heights (see Fig. 3(b) and (c)), because the thermalization effects exercised at all three levels (electron–spin–lattice) are caused by the energy pumped in the system and this disorganizing energy depends on the product of ($\tau_I$) and ($I$). In Fig. 2(d) is shown the temperature dynamics for low laser intensities ($I < I_0$) for which the thermalization effect is minimal. However, for the same durations and intensities the initial different temperatures variations can be observed. These differences will be reflected in a different shape of the switching regions associated with the duration ($\tau_I$) or the intensity ($I$).

4. Magnetization evolution and all-optical switching phase diagram

The evolution of the magnetization described through the present Metropolis Monte Carlo approach does not substantially differ from the one described by the Landau–Lifshitz–Bloch model [20]. In order to have an overview of the switching characteristics of the analyzed system, the simulation results were summarized in a phase diagram. For each relevant point on phase diagram several simulations were performed. If the magnetization orientation has not changed substantially, then the point in question corresponds to the no-switching region. If the magnetization orientation has changed its orientation in all cases, then, the point corresponds to the switching region. If the magnetization orientation has changed its orientation in some cases, then the point corresponds to the unstable switching region. The phase diagram of all-optical magnetization switching processes obtained through Monte Carlo analyze is shown in Fig. 3.

As it can be seen in Fig. 3, for the prolonged laser exposure or for high intensity, the temperatures become higher and the demagnetizing processes become dominant. Consequently, once the demagnetization state is reached, in the absence of an ordered effective magnetic field, the final magnetization orientation of the system is unpredictable, the situation which corresponds to the unstable switch region.

For very short duration or low intensity of laser pulses, both the system temperatures and the effective magneto-optical field do not significantly influence the magnetization of the system, this situation corresponds to the no-switching region. The stable switching is obtained for correlated values of laser pulse duration and intensity (see Fig. 3, stable switch region).

Even if the thermal effects of laser pulse duration and intensity on system temperatures are similar, the asymmetry observed for stable and unstable switch is explained by the fact that laser intensity ($I$) directly influences the effective magneto-optical field ($H_{EF}$), being an organizer parameter, while the pulse duration ($\tau_I$) induces directly thermal effects and indirectly switching effects. The asymmetry of phase diagram essentially reflects the competition between two distinct ways of energy transfer from the laser beam to the system: directly through helicity photon–electron momentum transfer and indirectly through photon–phonon conversion. It should be noted that the thermal effects are not only disordering actions but also facilitates the switching processes. To ensure the stability of all-optical switching...
it is necessary that laser intensity ($I$) and pulse duration ($\tau$) parameters correspond for the center of the stable switch region, thus ensuring that any perturbation is easily absorbed.

The present Monte Carlo simulations show that the results of this approach are consistent with both Landau–Lifshitz–Bloch modeling [20] and experimental findings [1].

Conclusions

Although Monte Carlo method is suitable to describe systems in equilibrium, with a proper calibration of Monte Carlo steps, the method proves to be quite accurate to describe the systems with pronounced dynamics.

For an accurate description of the all-optical switching with Metropolis Monte Carlo methods it was necessary to use a 4-temperature model which is an extension of the usual 3-temperature model by taking into account the medium constant temperature alongside with electron, spin and lattice temperatures.

In order to correlate temperature dynamics with spin dynamics of the calibration of Metropolis Monte Carlo model with Landau–Lifshitz–Bloch model by identifying the Monte Carlo steps needed for the same magnetization dynamics was required. In these conditions, the all-optical switching processes analyzed through Metropolis Monte Carlo model were determined to be in agreement with other modeling and experimental results.

By establishing the phase diagram associated with the all-optical switching system dynamics, it was possible to establish the limits of the phenomenon. In this respect, the phase diagrams revealed that there are three distinct regions: a region with certain switching, one with uncertain switching and another one, with no switching.

It has been found that the region with stable switching corresponds to a certain range of variations of laser pulse duration or intensity; the optimal parameters may be associated with the center of the region. The asymmetry of the phase diagram regions occurs in relation with different contributions to switching processes of the laser pulse duration and intensity parameters.

References