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ORIGINAL ARTICLE

Magnetization reversal in a site-dependent anisotropic Heisenberg ferromagnet under electromagnetic wave propagation

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Abstract Information density and switching of magnetization offers an interesting physical phenomenon which invoke magneto-optical techniques employed on the magnetic medium. In this paper, we explore the soliton assisted magnetization reversal in the nanosecond regime in the theoretical framework of the Landau–Lifshitz–Maxwell (LLM) model. Starting from the Landau–Lifshitz equation, we employ the reductive perturbation method to derive an inhomogeneous nonlinear Schrödinger equation, governing the nonlinear spin excitations of a site-dependent anisotropic ferromagnetic medium under the influence of electromagnetic (EM) field in the classical continuum limit. From the results, it is found that the soliton undergoes a flipping thereby indicating the occurrence of magnetization reversal behavior in the nanoscale regime due to the presence of inhomogeneity in the form of a linear function. Besides, the spin components of magnetization are also evolved as soliton spin excitations.

1. Introduction

The continuous effort in minimizing and search for ultimate speed of modern computers and magnetic recording media for data storage give rise to a constant strive to derive and potentially optimize mechanisms in order to manipulate fast reversal of magnetic moment of a material (see Fechner et al., 2012; Kaka and Russek, 2002; Tudosa et al., 2004;

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Adam et al., 2012; Schumacher et al., 2003). The interaction of light with matter spans a wide range of applications in all optical devices and has intensive focus in experimental research, with special attention paid to magnetization reversal that is running down to the limit of subpico/femtosecond regime. Generally, so-called magneto-optical switching combines the merits of magnetic and optical techniques and refers to a qualitative method of reversing magnetization in a ferromagnet simply by circularly polarized light, where the magnetization direction is controlled by the light helicity (see Stanciu et al., 2007a). In particular, the magnetization direction is well controlled by the direction of angular momentum of the photons (see Stanciu et al., 2006, 2007b). On theoretical grounds, it is shown that such effect may even lead the switching process down to femtosecond time scale that would be based on the application of shaped ultrashort laser pulse of certain frequency, duration and polarization (see Gmez-Abal et al., 2004). Experiments generally use pump-probe processes in which a high energy laser pulse is used to heat the sample and a low energy probe pulse is used to monitor the magnetic response using the magneto-optical Kerr effect (MOKE) (see Moradi and Ghanaatshoar, 2010; Chau and Hsieh, 1973; Liu et al., 2011; Montoncello et al., 2008; Georg and Back, 2007).

More qualitative features of the effect of laser on magnetization reversal can be well understood theoretically on the basis of electromagnetic wave equation proposed by Maxwell and Landau–Lifshitz (LL) equation that governs the spin dynamics of magnetic materials. The LL equation constitutes the basic governing equation for the spin–spin exchange interaction in ferro/antiferromagnet which includes crystal anisotropy with some other dominant higher order interactions namely biquadratic, weak interaction such as Dzyaloshinskii–Moriya (DM) interaction, dipole–dipole, and octupole–dipole interactions (see Daniel and Kavitha, 1999, 2002; Ahmad Abliz et al., 2009; Kavitha et al., 2010a,b, 2011a,b, 2012). Crystal field anisotropy being a primary interaction in all magnetic materials elucidates the spin reversal actively and simultaneously controls the characteristic switching time (see Uzdin et al., 2012). Moreover, higher order magnetic interactions also provide significant contribution for magnetization switching and the inhomogeneity present in the medium can too support for magnetization reversal as demonstrated by Kavitha et al., recently (see Kavitha et al., 2010a,b, 2011a,b, 2011). Thus the fundamental and the practical limit of speed of magnetization reversal is a subject of vital importance as well as one of the intriguing questions of modern magnetism.

In the above respect, recently the study of interaction of electromagnetic (EM) field in ordered magnetic media has become an emerging and growing field of research. In this case, the magnetic field component of the electromagnetic field is found to excite the magnetization of the ferromagnetic medium in solitonic form and also the small amplitude plane electromagnetic wave propagates in the form of EM solitons (see Leblond, 2005). Nakata (1991a,b) and Leblond (2008, 2010) also show the soliton excitations of EMW components in a ferromagnetic medium using a reductive perturbation method by neglecting the spin-spin exchange energy. Similarly an extension of the above investigation is made by taking into account the basic magnetic interaction namely the spin-spin exchange interaction in isotropic/anisotropic ferro and antiferromagnetic media (see Veerakumar and Daniel, 1998, 2001). Recently, the present authors made a rigorous study on the effect of DM interaction in an antiferromagnet (see Kavitha et al., 2011), thereby showing that DM interaction induces breatherlike spin excitations in the medium and in addition it enhances the amplitude of the EM soliton.

This paper communicates this issue and is constructed as follows. In Section 2, the coupled Landau–Lifshitz–Maxwell (LLM) equation is reduced to perturbed nonlinear Schrödinger (NLS) equation through the reductive perturbation method. In Section 3, we employ the multiple scale perturbation analysis on the perturbed NLS equation and obtain the soliton parameter evolution equations and magnetic spin soliton components are constructed. The occurence of magnetization reversal is discussed in Section 4. Section 5 concludes the results.

2. Model and spin dynamics

The system under consideration is a site-dependent anisotropic ferromagnetic medium exposed to an external magnetic field **H** through the propagation of electromagnetic wave governed by the Landau–Lifshitz equation for the evolution of spin density in the classical continuum limit. The dynamical equation is written as follows

$$\frac{\partial \mathbf{S}}{\partial t} = \mathbf{S} \times \{J(f\mathbf{S}_{xx} + f_x\mathbf{S}_x) - 2AS^x\hat{n} + 2\beta\mathbf{H}\}, \tag{1}$$

where $\hat{n} = (1, 0, 0)$ and suffix x represents partial differentiation, J is the exchange integral, f is the site dependent co-efficient which varies appropriately from site to site, A is the anisotropic parameter that tends the magnetization to favor along the x-direction and $\beta = \gamma\mu_B$, where, γ is the gyromagnetic ratio and μ_B represents Bohr magneton. In general the inhomogeneity occurs in the magnetic system if (a) the distance between neighboring atoms varies along the lattice, thereby altering the overlap of electronic wave functions, e.g. charge transfer complexes TCNQ or organometallic insulators TTF bisdithiolenes, and (b) the wave function itself varies from site to site although the atoms themselves may be equally spaced, e.g. a one-dimensional magnetic insulator placed in a weak, static, inhomogeneous electric field with the deliberate introduction of imperfections in the vicinity of a bond so as to alter the electronic wave functions without causing appreciable lattice distortion. Since the overlapping of wavefunction varies from site to site, the associated interaction is termed as 'site-dependent interaction' as designated by $f(x)$ in Fig. 1.

We consider the propagation of electromagnetic waves in a magnetic material medium in the presence of an external magnetic field. The governing Maxwell's equations are the following (see Jackson, 1993):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{2}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}. \tag{3}$$

In Eqs. (2) and (3), $\mathbf{E}, \mathbf{D}, \mathbf{H}$ and $\mathbf{B}$ are respectively the electric field, the electric induction, the magnetic field and the magnetic induction. The constitutive equation for **E** and **D** is

$$\mathbf{D} = \varepsilon\mathbf{E}, \tag{4}$$

where we shall assume that ε is the scalar permeability of the magnetic medium, whereas the constitutive equation for **H** and **B** is