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Inhomogeneous exchange within ferrites: Magnetic solitons and their interactions

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ABSTRACT

In the wake of the recent investigation of inhomogeneous exchange effects within ferrites [Kuetche et al., J. Magn. Magn. Mater. 3374 (2015) [1]], we pay a particular interest to the magnetic solitons and their dynamics. We study extensively the interactions between these waves while depicting the two-soliton features and the three-soliton scattering scenarios of the waveguides. As a result, we find that these typical head-on collisions are actually elastic. Discussing deeply the results, we determine the individual shifts of the interacting waves and we find that they actually comprise two parts: the first one relates to the nonlinear character of the interactions and the second one characterizes the motion of the smaller soliton along the larger one. Additionally, we depict the energy density of the interacting waves and we address the physical implications of the previous results.

1. Introduction

In relation with the increasing interests in advanced magnetic information storage and data process element, a proper and detailed understanding of the micromagnetic structure in microsized and nanosized magnets becomes more crucial. In the wake of these interests, Kuetche et al. [1] regarded recently in a leading attempt a ferromagnetic slab of 0.5 mm thickness while investigating deeply the effects of inhomogeneous exchange within the material. As a result, they derived the governing coupled system given by [1]

$$B_{xt} = BC_x + \varrho B_{xx} - sB_x, \tag{1a}$$

$$C_{xt} = -BB_x, \tag{1b}$$

arising from the nonlinear dynamics of magnetic polaritons in the medium. The variables x and t are generic spacelike and timelike coordinates, respectively, while the physical meanings of the observables B and C will be reviewed briefly in the next section. The constant s is the first-order dimensionless Gilbert-damping parameter and the quantity ϱ stands for an arbitrary parameter expressed in term of the second-order dimensionless inhomogeneous exchange parameter within the magnet.

Already at the heart of the information technologies developed in the second half of the twentieth century, the tailoring of magnetic materials [2–4] is arguably undergoing a second revolution with the development of spintronics [5,6]. Below the Curie transition temperature, the spin degrees of freedom carried by localized electrons in ferromagnetic materials tend to spontaneously long-range order. Micromagnetic description actually consists in studying the local order parameter – the magnetization averaged over a few lattice cells.

In solid physics, the understanding of complex magnetic structures can be achieved by the Heisenberg model of spin–spin interactions. Such a model has successfully explained the existence of ferromagnetism below the Curie temperature, and also attracted considerable attention in nonlinear science and condensed matter physics [7]. The dynamics and kinetics of a ferromagnet is dictated by the variations in its magnetization. When a ferromagnet is used to store information, bits are encoded in the orientation of the local magnetization. Controlling the state of a ferromagnet crystal unambiguously described by the magnetization vector stands to be fundamental in the understanding of the magnetic storage process of the data elements. Different aspects of magnetization dynamics are involved in magnetic storage technologies in extended layers and nanostructures [8–12]. Investigating the magnetic nanoelements is not only in focus in view of their technological potential but they are often as test systems

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for the analysis of debated microscopic mechanisms involved in magnetization dynamics such as coupling to spin-currents [13–15], heat gradients [16] and the role of spin–orbit coupling in domain wall dynamics [17,18], just to name a few. Dissipation – relaxation of excited magnetic textures towards an equilibrium state – is faced usually when magnetic textures are dynamically manipulated.

Actually, magnetization dissipation, expressed in terms of the Gilbert-damping parameter, is a key factor determining the performance of magnetic material in a host of applications. As a matter of fact, we mention the enhancement of the damping of ferromagnetic materials in contact with nonmagnetic metals [19,20] in magnetic memory devices based upon ultrathin magnetic layer [21,22], which paves the way to tailoring the Gilbert-parameter for particular materials and applications.

Nonlinear behavior in magnetic systems actually constitutes a great topic of continuing interest [23–25]. There has been a number of experiments [26–28] which have shown an interesting nonlinear mixing of two signals in magnetic materials. The tradeoff between the nonlinearity – tendency to increase the wave slope and the dispersion – tendency to flatten the wave generates some typical self-confined structures coined as solitons. In ferromagnetism, these structures known as magnetic solitons are sometimes referred to magnons. Owing to attraction, a cluster of magnons in ferromagnetism tends to be self-localization. In one-dimensional ferromagnets, the previous attraction becomes critical due to the fact that it produces a bound state of quasi-particles. Because of the self-localization of the magnon cluster, a spin wave which can be regarded as a cluster of microscopic number of coherent magnons becomes unstable. The topological soliton and the dynamic soliton [29] are the result of the magnetization localization induced by the developing instability. The topological soliton which refers to the magnetic domain wall is regarded as a potential hill separating two degenerated magnetic states. This type of soliton actually forms a spatially localized configuration of magnetization where the magnetic moments inverse gradually. The second type describes the localized states of magnetization which is likely to reduce to a uniform magnetization by continuous deformation where the excited ferromagnet transits to the ground state. These typical solitons which result from the tradeoff between the Maxwell equations and the Landau–Lifshitz–Gilbert equation constitute a family of waves known as autonomous solitons which are similar to the classical soliton concept introduced firstly by Zabusky and Kruskal [30] for autonomous nonlinear and dispersive dynamic systems [31,32]. They can completely preserve their localized form and speed during propagation and even after suffering some complex head-on collision with one another.

Since bits are encoded in the orientation of the local magnetization, our main motivation in this work is to better understand the magnetic information storage and data process elements in advanced magnetic devices. Thus, our leading objective is to investigate properly the dynamics of a ferromagnet slab of zero conductivity where inhomogeneous exchange becomes crucial. We are then resorted to study properly the governing system above given by Eq. (1), from the physical viewpoint consisting of the propagation and nonlinear interactions between the magnetic polaritons within the slab. Accordingly, we organize our work as follows. In Section 2, we review in a concise presentation the physical ground of the system given by Eq. (1). Next, in Section 3, we study the soliton structure of the previous system while expressing in detail the two-soliton and the three-soliton solutions alongside their energy functionals – kinetic, potential, and total energy densities. Then, in Section 4 we discuss the above results while computing the shifts of the individual solitons. Finally, we end the present work with a brief summary.

2. Physical ground: inhomogeneous exchange within ferrites

We consider a quasi one-dimensional ferrite slab lying in the x-axis, the transverse dimension being negligible. This slab is magnetized to saturation by an in-plane external field $\mathbf{H}_0^\infty$ directed along the transverse y-axis perpendicular to the propagation x-direction as presented in Fig. 1. Due to the absence of eddy currents, electromagnetic waves are likely to propagate. We consider a thick enough film in view of ensuring a homogeneous magnetization over the ferrite. We assume that the crystalline and surface anisotropy of the sample is negligible. The use of Maxwell's equations combined to the Landau–Lifshitz–Gilbert (LLG) equation [33,34] for a ferrite yields the following dimensionless system

$$-\nabla\cdot(\nabla\cdot\mathbf{H}) + \Delta\mathbf{H} = \partial_t^2(\mathbf{H} + \mathbf{M}), \tag{2a}$$

$$\partial_t\mathbf{M} = -\mathbf{M}\wedge\mathbf{H}_{\text{eff}} + \sigma\mathbf{M}\wedge\partial_t\mathbf{M}/m, \tag{2b}$$

where vectors $\mathbf{H}$ and $\mathbf{M}$ stand for the dimensionless magnetic induction and magnetization density, respectively. From a practical viewpoint, the above coupled equations are actually fundamental for investigation of the data loading processes in reversal magnetic memory devices in the ferrites. The constants m and σ refer to the dimensionless saturation magnetization and Gilbert-damping parameter [33,34], respectively.

The expression of the effective field $\mathbf{H}_{\text{eff}}$ is given by [33,34]

$$\mathbf{H}_{\text{eff}} = \mathbf{H} - \beta\mathbf{n}(\mathbf{n}\cdot\mathbf{M}) + \alpha\Delta\mathbf{M}, \tag{3}$$

where α and β are the constants of the inhomogeneous exchange and the magnet anisotropy, respectively, and $\mathbf{n}$ is the unit vector directed along the anisotropy axis. For a simple tractability, we assume $\mathbf{n} \equiv e_z$ directed along the z-axis.

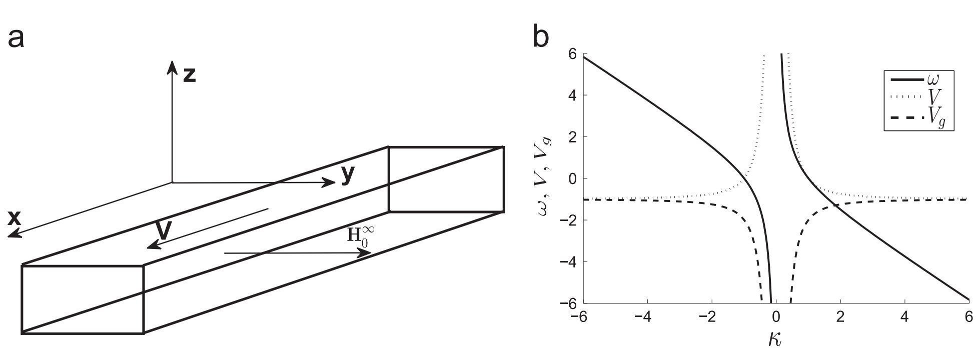

Fig. 1. Ferrite slab and dispersion relation. In panel (a), vectors **V** and $\mathbf{H}_0$ stand for the velocity of the wave propagation and the in-plane external magnetic field, respectively. In panel (b), the variations of the wave-frequency ω, the phase velocity V of the plane wave, and the group velocity V_g of the bulk wave are plotted against the wave-number κ of the wave.