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Investigation of effects of inhomogeneous exchange within ferrites

Victor K. Kuetche [a,b,c,d], Francis T. Nguepjouo [a,b,c], Timoleon C. Kofane [b,c,d]

[a] National Advanced School of Engineering, University of Yaounde I, P.O. Box 8390, Cameroon
[b] Centre d'Excellence en Technologies de l'Information et de la Communication (CETIC), University of Yaounde I, P.O. Box 812, Cameroon
[c] Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812, Cameroon
[d] The Abdus Salam International Centre for Theoretical Physics (ICTP), Strada Costiera, 11-I-34151 Trieste, Italy

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ABSTRACT

In this paper, we investigate the effects of inhomogeneous exchange on the magnetization dynamics within a ferromagnetic slab of 0.5 mm thickness from the viewpoint of the Landau–Lifshitz–Gilbert phenomenological theory of damping in ferromagnets. As a result, we unearth a new coupled system of magnetization dynamics in which structural analysis reveals the existence of soliton propagation in the above ferrite.

1. Introduction

Electromagnetic wave propagation in ferro- or ferrimagnetic media is highly nonlinear and produces soliton solutions in these dispersive materials (see Ref. [1] and references therein). These structures have been predicted theoretically [2–5] and observed experimentally [6–8] for a long time. In fact, the study of electromagnetic wave propagation is not only of interest theoretically but also practically, particularly in connection with the behavior of ferrite devices at microwave frequencies such as ferrite-loaded waveguide [9]. In fact, ferrites have proven efficient as microwave materials, and Harris et al. [10] have brought together researchers from various places on three continents to evidence that these materials also have brilliant future. Significant advances have been obtained in recent years: novel preparation processes are available, and new devices have been proposed and are successfully operated. The many properties available through the great variety of compositions provide remarkable engineering possibilities [11,12].

With the increasing interest in advanced magnetic information storage and data process elements, it appears fundamental and more crucial to understand deeply the micromagnetic structures in microsize and nanosize of magnets [13–16]. Some developed nanofabrication techniques have made possible to generate ferromagnet particles to a length of 20–30 nm [13]. Owing to the relatively small size of such nanoparticles, the magnetization can be regarded as homogeneous over a particle and can be described by magnetic moment. These particles interact with each other through a dipolar interaction of the magnetic moments and the solitons originating from this interaction are stably created [13].

Basically, the understanding of the electromagnetic propagation in ferromagnetic materials is actually made possible by Maxwell's equations in such media. These equations are supplemented with a relation between the magnetization and the auxiliary magnetic field in the materials. Such a relation appears as the phenomenological equation of motion for the magnetization. A physical description of the micromagnetic phenomena is based on the use of the Landau–Lifshitz–Gilbert (LLG) equation controlling the magnetic relaxation process and determining how fast the magnetization is restored to its equilibrium position [17,18]. As far as we are concerned, no fully analytical theory has been developed so far to solve the above equations. Nonetheless, in view of obtaining results valid in nonlinear regimes, one has to resort to intermediate models where a novel perturbative parameter most often of longness or shortness of the wave is introduced [19].

In this work, we restrict our interest to the propagation of short-waves in a saturated ferrite only in the direction perpendicular to the external saturating magnetic field. Granted this consideration is satisfied, the nonlinear dynamics actually obey an evolution system in which the structure can be investigated by means of the initial value analysis. The technique adopted in the paper is quite detail and also includes some recent relevant references [20].

E-mail addresses: vkuetche@yahoo.fr (V.K. Kuetche), nguepjouofrancis@yahoo.fr (F.T. Nguepjouo), tckofane@yahoo.com (T.C. Kofane).

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The organization of this paper is settled as follows. In Section 2, taking into account of inhomogeneous exchange within the ferrite, we derive an evolution model system governing the propagation of short-waves in the material. In Section 3, looking forward to accessing the effects of the inhomogeneous exchange upon the magnetization dynamics, we investigate the initial value problem of the new system above. Finally, we end this work with a brief summary.

2. Inhomogeneous exchange in ferrites

Let us consider a lower-dimensional ferrite slab lying in the x-axis, the transverse dimension being negligible. Such a configuration considered in this paper is presented in Fig. 1 where the slab thickness is typically about 0.5 mm assumed to be large with respect to the wavelengths in the range 1–100 μm. 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. In such condition, due to the absence of eddy currents, electromagnetic waves are likely to propagate. Thus, it is obvious to show that out of any current and charges in the ferromagnet, the Maxwell equations in the previous media of scalar permittivity ϵ_0 reduce to

$$-\nabla\cdot(\nabla\cdot\mathbf{H})+\Delta\mathbf{H}=\partial_t^2(\mathbf{H}+\mathbf{M})/c^2, \quad (1)$$

where $c=1/\sqrt{\mu_0\epsilon_0}$ is the speed of light, μ_0 being the magnetic permeability of the vacuum, and the vectors $\mathbf{H}$ and $\mathbf{M}$ stand for the magnetic induction and the magnetization density, respectively.

In this work, on a phenomenological level, we assume a fast near-adiabatic magnetization dynamics described by the Landau–Lifshitz–Gilbert equation for the magnetization given by [17,18]

$$\partial_t\mathbf{M}=-\gamma\mu_0\mathbf{M}\wedge\mathbf{H}_{\text{eff}}+\sigma\mathbf{M}\wedge\partial_t\mathbf{M}/M_s, \quad (2)$$

where the first term on the right-hand side (γ being the gyromagnetic ratio) describes the precession of the magnetization around the micromagnetic effective field $\mathbf{H}_{\text{eff}}$, and the second term which is the Gilbert-damping term (with the damping parameter σ) drives the magnetization towards the direction of $\mathbf{H}_{\text{eff}}$, whereby angular momentum is transferred to nonmagnetic degrees of freedom. The quantity M_s represents the saturation magnetization. The expression of the effective field $\mathbf{H}_{\text{eff}}$ is given by [17,18]

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

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. It is important to transform the above systems to dimensionless equation for a proper investigation. Thus, following the transformation:

$$\mathbf{M}\to c\mathbf{M}/\mu_0\gamma,\quad \mathbf{H}\to c\mathbf{H}/\mu_0\gamma,\quad t\to t/c, \quad (4)$$

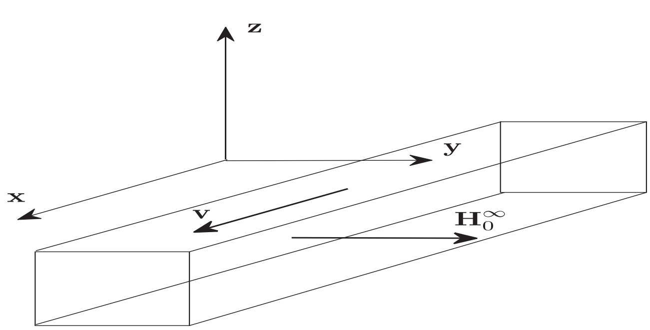

Fig. 1. Configuration considered. Vectors $\mathbf{v}$ and $\mathbf{H}_0$ stand for the velocity of the wave propagation and the in-plane external magnetic field, respectively.

Eqs. (1) and (2) retain the same forms provided to replace the quantities $\mu_0\gamma/c$ and c by 1, and the saturation magnetization M_s by $m=\mu_0\gamma M_s/c$, separately. Next, we shall assume the subscripts to the observable as the partial derivatives with respect to the corresponding variables.

While treading into the understanding of the inhomogeneous exchange within the ferrite, it seems to be useful to first investigate the linear limit regime of the system. As the sample is supposed to be magnetized to saturation by means of an external uniform field, we arguably choose the steady state

$$\mathbf{M}_0=(m\cos\theta, m\sin\theta, 0),\quad \mathbf{H}_0=\mu\mathbf{M}_0, \quad (5)$$

where μ is the strength of the internal magnetic field, θ being the angle between the dominant propagation direction x-axis and the internal magnetic field. Let us linearize the dimensionless counterparts of Eqs. (1) and (2) obtained previously around the above state and consider the plane wave perturbation solution propagating along the x-direction such as

$$\mathbf{M}=\mathbf{M}_0+\epsilon\mathbf{M}_1\exp[\imath(kx-\omega t)],$$
$$\mathbf{H}=\mathbf{H}_0+\epsilon\mathbf{H}_1\exp[\imath(kx-\omega t)], \quad (6)$$

where quantities k and ω are the wave number and the frequency of the wave, respectively, ϵ being the perturbation related to the shortness of the wave. Vectors $\mathbf{M}_1$ and $\mathbf{H}_1$ are arbitrary real scalar quantities with three constants components each. Accordingly, the parameters α and β also suffer expansion with respect to ϵ as

$$\alpha=\sum_{i=0}^{\infty}\alpha_i\epsilon^i,\quad \beta=\sum_{i=0}^{\infty}\beta_i\epsilon^i,\quad \sigma=\sum_{i=0}^{\infty}\sigma_i\epsilon^i. \quad (7)$$

Replacing Eqs. (6) and (7) into the governing system of dynamics, in the linear limit, we derive the following dispersion relation of linear waves propagating over the steady state as follows:

$$\omega^2(\omega^2-k^2)^2+m^2\{(\tilde{\alpha}+\beta_0)(\omega^2-k^2)+\omega^2\}$$
$$\{k^2\sin^2\theta-[\tilde{\alpha}(\omega^2-k^2)+\omega^2]\}=0, \quad (8)$$

where

$$\tilde{\alpha}=\mu+\alpha_0k^2-\imath\omega\sigma_0/m. \quad (9)$$

As mentioned previously, we are interested in studying the short-wave limit $k\to\infty$. Thus, assuming the perturbation ϵ as the shortness of the plane wave, it comes that $k\sim\epsilon^{-1}$ with $\epsilon\ll 1$. Consequently, the frequency expands accordingly as

$$\omega=\omega_{-1}\epsilon^{-1}+\omega_1\epsilon+\omega_2\epsilon^2+\omega_3\epsilon^3+\cdots. \quad (10)$$

It should be emphasized that the previous assumption corresponds just to the requirement that short-waves exist in the linear limit with the phase velocity and the group velocity always bounded.

Now, replacing Eq. (10) into the dispersion relation above, we obtain a set of equations

- At order of ϵ^{-8}:

$$\omega_{-1}=\pm k_0. \quad (11)$$

- At order of ϵ^{-4}:

$$\texttt{Either}\ 1+2\omega_{-1}\omega_1\alpha_0=0, \quad (12a)$$

$$\texttt{or}\ 1+2\omega_{-1}\omega_1\alpha_0=\sin^2\theta. \quad (12b)$$

- At order of ϵ^{-3}:

$$\texttt{Either}\ \sigma_0=0\quad \texttt{or}\quad 2(1+2\omega_{-1}\omega_1\alpha_0)=\sin^2\theta. \quad (13)$$

- At order of ϵ^{-2}:

$$4k_0^2\omega_1^2+m^2\{-(1+2\omega_{-1}\omega_1\alpha_0)[2\omega_{-1}\omega_1(1+\mu)$$