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Research paper

Spin waves in a two-sublattice antiferromagnet. A self-similar solution of the Landau-Lifshitz equation

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ABSTRACT

In the paper, spin waves in a uniaxial two-sublattice antiferromagnet are investigated. A new class of self-similar solutions of the Landau-Lifshitz equation is obtained and, therefore, a new type of spin waves is described. Examples of solutions of the found class are presented. New type of solution admits both linear and non-linear spin waves, including solitons. Space transformations used in the solution are mathematically analogous to the relativistic transformations.

1. Introduction

Waves of magnetization in magnetically ordered materials – so-called spin waves [1] – have been investigated intensively during last decades, both theoretically and experimentally. There are numerous articles dedicated to spin waves in various types of media [2,3], to the processes of reflection and passage of spin waves on the interface of two media [4,5] and so on. In particular, a number of articles are dedicated to nonlinear spin waves, including spin solitons [6]. (Investigation of spin solitons in magnetics is important because their presence change properties of the magnetic.) Spin waves – in particular, nonlinear spin waves – are promising for a variety of practical applications: creation of new information transfer and storage devices [1,7–9], creation of new computing devices [10] and so on. Moreover, new fields of research and technology that study spin waves appeared recently – magnonics [11] and spintronics [12].

Up to recently, spin-wave electronics dealt mostly with spin waves in ferromagnets. Antiferromagnets, however, are prospective new materials for spin-wave electronics with a variety of possible technical applications (mostly in data storage, transmission and processing devices). Generation and detection of spin waves in antiferromagnets in recent years [13,14] made these technical applications possible. Unlike the ferromagnetic materials, antiferromagnets don't possess strong macroscopic intrinsic magnetic field, applications of antiferromagnets allow use of semiconductor materials and, most importantly, antifferomagnets allow higher working frequencies compared to ferromagnets [15]. In recent years, during investigation of spin waves in antiferromagnets nonlinear spin waves (with unique properties that are not inherent to linear spin waves) were also generated and investigated [16–18]. Therefore, investigation of spin waves in antiferromagnets – especially of new types of nonlinear spin waves that can be excited in antiferromagnets – is an actual topic of research.

In the paper, spin waves in a uniaxial two-sublattice antiferromagnet are investigated. A system of equations for the antiferromagnetic vector obtained from the Landau-Lifshitz equation (see, e.g., [19]) is used. After substituting a self-similar

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form of the dependence of the antiferromagnetic vector on the time and space coordinates, a system of equations for the azimuthal and polar angles of the antiferromagnetic vector is obtained. For this system of equations, a new class of solutions is proposed; this class of solutions allows non-linear waves, including solitons. Three cases are investigated: the spin wave velocity exceeds the characteristic velocity, the characteristic velocity exceeds the spin wave velocity and both velocities are equal (in the last case, no solution of the above-described type is possible). Examples of the solutions of the new obtained class are presented and illustrated.

2. Problem statement

Let us consider a uniaxial two-sublattice antiferromagnet. Let us assume that the magnetization densities of the antiferromagnet sublattices ($\vec{M}_1$ and $\vec{M}_2$, respectively) are equal in magnitude and opposite in direction ($\vec{M}_1 = -\vec{M}_2$). Let us also assume that they are constant in magnitude ($|\vec{M}_1| = |\vec{M}_2| = M_0$, M_0=const). Thus, the total magnetization vector $\vec{M} = 0$. (In the third section of this paper we also consider a nonzero magnetization vector. However, the considered magnetization vector is small in magnitude$-\vec{M}^2 << \vec{L}^2$, where $\vec{L}$ is the antiferromagnetic vector – and is neglected afterwards). The antiferromagnetic vector is also constant in magnitude: $|\vec{L}| = L_0 = const$. Let us denote the antiferromagnet parameters as follows: the uniaxial anisotropy constants of the sublattices β_1 and β_2, the non-uniform exchange constants of the sublattices α_1 and α_2 (here $\alpha_1 > 0$), the uniform exchange constant A.

Let us consider a spin wave propagating in the above-described antiferromagnet. Let us use the spherical coordinates (r,θ,φ) and denote the azimuthal and polar angles of the vector $\vec{L}$ as θ_L and φ_L, respectively. Therefore,

$$\vec{L} = L_0(\vec{e}_x sin\,\theta_L cos\phi_L + \vec{e}_y sin\,\theta_L \sin\phi_L + \vec{e}_z cos\theta_L) \tag{1}$$

where $\vec{e}_x$, $\vec{e}_y$ and $\vec{e}_z$ are the unit vectors of the Ox, Oy and Oz axes, correspondingly. The absolute value of the azimuthal angle θ_L cannot exceed π. The polar angle φ_L can be considered unlimited after noticing that it possesses a periodicity (with the period equal to 2π).

The task of the current paper is to obtain self-similar solutions for the azimuthal and polar angles of the antiferromagnetic vector for the above-described – generally speaking, non-linear – spin wave in the antiferromagnet.

3. Self-similar solution of the Landau-Lifshitz equation

3.1. System of equations for the azimuthal and polar angles of the antiferromagnetic vector

In order to investigate spin dynamics of the antiferromagnet described in the previous section, let us write down an energy functional for the ferromagnet and substitute it into the Landau-Lifshitz equation.

Magnetic energy in a uniaxial antiferromagnet has the following form:

$$W = \int dV \left(\frac{1}{2} A\vec{M}^2 + \frac{1}{2}\alpha_1 \sum_i \left(\frac{\partial \vec{L}}{\partial x_i} \right)^2 + \frac{1}{2}\alpha_2 \sum_i \left(\frac{\partial \vec{M}}{\partial x_i} \right)^2 - \frac{1}{2}\beta_1 L_z^2 - \frac{1}{2}\beta_1 M_z^2 - \vec{M}\vec{H}_0 \right) \tag{2}$$

(here we still consider a nonzero magnetization: $\vec{M}^2 << \vec{L}^2$). Here $\vec{H}_0$ is the external magnetic field, and the integration is performed over the entire antiferromagnet volume.

Using the Landau-Lifshitz equation for a two-sublattice antiferromagnet (see, e.g., [19]) in the long-wave approximation with the energy functional (2), we obtain for the antiferromagnetic vector

$$\frac{\hbar}{2\mu_0}\frac{\partial \vec{L}}{\partial t} = \left(\vec{H}_0 - A\vec{M} \right) \times \vec{L} \tag{3}$$

or, after considering $\vec{M}^2 \ll \vec{L}^2$,

$$\vec{M} = \frac{\hbar}{8\mu_0 A M_0^2}\left[\frac{\partial \vec{L}}{\partial t} \times \vec{L} \right] + \frac{1}{4AM_0^2}\left[\vec{L} \times \left[\vec{H}_0 \times \vec{L} \right] \right], \tag{4}$$

and for the magnetization vector

$$\frac{\hbar}{2\mu_0}\frac{\partial \vec{M}}{\partial t} = \alpha_1 [\vec{L} \times \Delta \vec{L}] + [\vec{M} \times \vec{H}_0] + \beta_1 L_z [\vec{L} \times \vec{e}_z] \tag{5}$$

(in the same approximation). After substituting the Eq. (4) into (5) the magnetization is eliminated. Therefore, we obtain the following equation for the antiferromagnetic vector dynamics (analogous to the one obtained by Kosevich et al. [19]):

$$\left[\vec{L} \times \left(c^2 \Delta \vec{L} - \frac{\partial^2 \vec{L}}{\partial t^2} \right) \right] = \frac{4\mu_0}{\hbar}\left(\vec{L} \cdot \vec{H}_0 \right)\frac{\partial \vec{L}}{\partial t} + \frac{4\mu_0^2}{\hbar^2}\left(\vec{L} \cdot \vec{H}_0 \right)\left[\vec{L} \times \vec{H}_0 \right] - \omega_0^2 L_z \left[\vec{L} \times \vec{e}_z \right], \tag{6}$$

here $\omega_0 = \frac{4\mu_0 M_0}{\hbar}\sqrt{A|\beta_1|}$.