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Prospects for the application and properties of spin waves

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The paper investigates the dispersion properties of spin waves by linearizing the LLG equation, which is applied to long samples with transverse dimensions on the nanometer scale, assuming their polycrystalline structure. The obtained dispersion law generally coincides with the result of another well-known theoretical model of spin wave propagation, the Kallinikos-Slavin model. The model limitations caused by such assumptions as: absence of Hilbert damping and absence of internal anisotropy (polycrystallinity) are analyzed. Quantitative characteristics are obtained for the most common magnetic materials in practical applications, on the basis of which potential frequency ranges are identified in which the exchange interaction prevails and in which the quadratic law of spin wave dispersion is revealed. The results obtained are promising for future generations of telecommunications technologies and biochemical research due to the well-predicted properties of spin waves and the possibility of miniaturization of devices for detecting electromagnetic radiation in the gigahertz range.

Keywords polycrystalline magnetic samples, spin waves, scalar magnetic potential, homogeneous wave, exchange interaction.

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Introduction

The development of theoretical models of the interaction of electromagnetic oscillations and matter can be divided into two directions: classical or semiclassical theory, based on the Landau-Lifshitz and Hilbert equations, and quantum theory, based on magnons. The main conclusions of the semiclassical theory are the existence of two branches of the dispersion dependence of oscillations in magnetic materials - magnetostatic and exchange, which arises with an increase in the wave number. Depending on the wave number, magnetostatic waves without exchange interaction, magnetostatic waves with exchange interaction, and waves with the dominance of exchange dipole-dipole interaction, which have a large wave number, are distinguished. Magnetostatic waves with exchange interaction and waves with dominant exchange interaction have the general name: the spin

waves. Their most interesting feature from a practical point of view is that the wavelength is smaller compared to the length of the electromagnetic wave. This allows miniaturization of the size of devices for detecting microwave and millimeter ranges [1]. Current research also shows that the efficiency of converting electromagnetic energy into spin wave energy can reach 75 percent [2]. The size of the detection devices will also be limited by the distance at which the spin wave has sufficient amplitude to be detected. This distance varies significantly for known magnetic materials: from micron sizes for Py to millimeter sizes for YIG.

The properties of spin waves are usually modeled within the framework of a macroscopic theory based on the Landau-Lifshitz-Hilbert equation. This theory explains such complex phenomena as the emergence of solitons in chiral magnets [3], the emergence of skyrmions in twisted magnetic nanowires [4], and nonlinear magnetization dynamics [5]. However, quantum theory

also describes spin waves and related phenomena that arise as a result of exchange interactions well. The most developed models within the framework of the quantum approach are the theories of nanooscillators and resonators [6].

One of the reasons that stand in the way of the development of holistic theoretical ideas about spin waves and phenomena caused by their occurrence is the difficulty of conducting experimental studies, as a result of which we learn about certain properties of these waves. Like any wave process, a spin wave is characterized by such parameters as: its frequency, wavelength, type of oscillations - longitudinal or transverse, and the type of polarization of this wave. Only recently, thanks to the improvement of manufacturing technologies and measurements of magnetic materials, experimental results of studies of polarization properties of spin waves have appeared [7]. Thanks to the improvement of the methodology for conducting X-ray structural studies in magnetic materials, it has become possible to obtain experimental results of the propagation of spin waves in bulk materials [8], while the majority of other methods detect only processes occurring on the surface of samples. To study the processes of spin wave propagation in bulk material, the Fourier transform method is used [6], which helps to understand the patterns of propagation in periodic nanostructures.

The processes of converting electromagnetic radiation into a spin current and detecting this current [9] have a wide range of promising applications - from radar and antenna technology, where controlled processes of generating spin waves make it possible to significantly reduce geometric dimensions and energy consumption; scientific research related to high-precision detection of microwave electromagnetic fields [10]. Recent research on biomedical sensors makes it possible to predict the emergence of a new class of sensitive biosensors that use ferromagnetic resonance in the gigahertz frequency range [11, 12].

I. Theoretical framework

The basis of most methods for simulating a spin wave is the Landau-Lifshitz-Gilbert equation, which describes the precession of the magnetization vector $\vec{M}$ of a sample in an external magnetic field $\vec{H}_{eff}$:

$$\frac{\partial \vec{M}}{\partial t} = \gamma \cdot \mu_0 \cdot \vec{H}_{eff} \times \vec{M} + \frac{\alpha}{M_s} \cdot \vec{M} \times \frac{\partial \vec{M}}{\partial t} \quad (1)$$

where α – Gilbert damping constant, γ – gyromagnetic ratio, $\vec{M}$ – the variable magnetization vector of the sample, $\vec{H}_{eff}$ – the effective magnetic field in the sample, $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$ – the magnetic constant, M_s – the critical value of magnetization, which depends on the material (Table 1).

The most comprehensive model that accounts for the formation of the effective magnetic field $\vec{H}_{eff}$, is expressed as the sum of the following components:

$$\vec{H}_{eff} = \vec{H}_0 + \vec{H}_{ex} + \vec{H}_m + \vec{H}_{an,sh} + \vec{H}_{an,i} \quad (2)$$

where $\vec{H}_0$ – the vector of the externally applied magnetic field; $\vec{H}_{ex}$ – the exchange interaction field; $\vec{H}_m$ – the magnetostatic demagnetizing field, caused by the stable state of internal magnetization in ferromagnetic samples; $\vec{H}_{an,sh}$ – the field associated with shape anisotropy; $\vec{H}_{an,i}$ – the field associated with crystalline anisotropy.

The crystalline anisotropy factor can be neglected if the sample is polycrystalline.

We further assume that for a polycrystalline sample the internal anisotropy field $\vec{H}_{an,i}$ can be neglected. In this model, we also neglect the damping of oscillations in the sample. According to the classical ideas within the framework of the LLG model, taking into account the Gilbert coefficient leads only to an exponential damping of the wave amplitude in the direction of its propagation, without changing its other properties. In the case of more accurate models, it is necessary to take into account specific causes and scattering mechanisms that can change these ideas [14].

Regarding the effect of shape anisotropy: for a sample with one geometric dimension significantly larger than the other two (a rod), the vector Hilbert equation can be written as a system of equations describing the oscillations of the magnetization vector in directions perpendicular to the wave propagation (transversely polarized wave) [15, 16]. The corresponding mathematical transformations are given in the next section.

The demagnetization magnetic field $\vec{H}_m$ is expressed in terms of the magnetostatic potential φ of the sample:

$$\vec{H}_m = -\nabla\varphi \quad (3)$$

$$\vec{H}_{eff} = \vec{H}_0 + \vec{H}_{ex} + \vec{H}_m = \vec{H}_0 + \frac{2 \cdot A_{ex}}{\mu_0 M_s^2} \cdot \Delta \vec{M} - \nabla\varphi, \quad (4)$$

where A_{ex} is the exchange interaction constant, M_s is the critical value of the sample magnetization, and φ is the magnetostatic potential.

A summary list of constants and values used in this work is given in the Table 1.

Table 1.

Physical quantities and constants used in the work

№	Designation	Name	Value, units
1	α	Gilbert constant	$\alpha \approx 0$
2	γ	gyromagnetic ratio	$2\pi \cdot 28 \times 10^9, \text{ Hz/T}$
3	μ_0	permeability	$4\pi \times 10^{-7}, \text{ H/m}$
4	A_{ex}	exchange stiffness	$p\text{J/m}$
5	M_s	critical magnetization	$k\text{A/m}$
6	$\vec{M}$	magnetic moment	$k\text{A/m}$
7	m_x, m_y	variable components of the magnetic moment	A/m
8	φ	magnetostatic potential	A

II. Results

Thus, the vector equation to be linearized has the form:

$$\frac{\partial \vec{M}}{\partial t} = \left(\vec{H}_0 + \frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s^2} \cdot \Delta \vec{M} - \nabla \varphi \right) \times \gamma \cdot \mu_0 \cdot \vec{M}. \quad (4)$$

Regarding the influence of shape anisotropy, for a sample with one geometric dimension significantly exceeding the other two (a rod), the vector LLG equation can be written as a system of equations describing the oscillations of the magnetization vector in directions perpendicular to the wave propagation (Fig. 1).

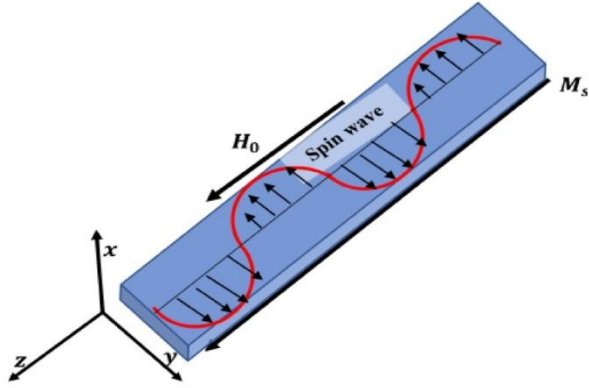


Fig. 1. Schematic illustration of a uniformly magnetized polycrystalline rod and the propagation of a transverse spin wave with circular polarization.

Next, we find the components of the vector quantities in equation (4):

$$\vec{H}_0 = (0, 0, H_0), \quad \vec{M} = (m_x, m_y, M_s), \quad (5)$$

$$\Delta \vec{M} = \left(\frac{\partial^2 m_x}{\partial x^2} + \frac{\partial^2 m_x}{\partial y^2} + \frac{\partial^2 m_x}{\partial z^2}, \frac{\partial^2 m_y}{\partial x^2} + \frac{\partial^2 m_y}{\partial y^2} + \frac{\partial^2 m_y}{\partial z^2}, 0 \right) \quad (5a)$$

$$\nabla \varphi = \left(\frac{\partial \varphi}{\partial x}, \frac{\partial \varphi}{\partial y}, \frac{\partial \varphi}{\partial z} \right) \quad (56)$$

If the wave propagates along the z axis (wave vector $\vec{k} || z$), then:

$$\frac{\partial^2 m_x}{\partial z^2} = -k^2 \cdot m_x, \quad \frac{\partial^2 m_y}{\partial z^2} = -k^2 \cdot m_y, \quad (6)$$

where k is the wave number of the spin wave.

Thus, we find the components of the magnetic field $\vec{H}_{eff} = (H_x, H_y, H_z)$:

$$\begin{cases} H_x = \frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s^2} \cdot \left(-k^2 + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) m_x - \frac{\partial \varphi}{\partial x} \\ H_y = \frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s^2} \cdot \left(-k^2 + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) m_y - \frac{\partial \varphi}{\partial y} \\ H_z = H_0 - \frac{\partial \varphi}{\partial z} \end{cases} \quad (7)$$

Next, projecting the vector equation (4), we obtain two scalar equations, since $\vec{M}_z \approx M_s = \text{const}$:

$$\begin{cases} \frac{\partial m_x}{\partial t} = \gamma \cdot \mu_0 \cdot \left\{ -H_0 + \frac{\partial \varphi}{\partial z} + \frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s} \cdot \left(-k^2 + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \right\} \cdot m_y - M_s \cdot \frac{\partial \varphi}{\partial y} \\ \frac{\partial m_y}{\partial t} = -\gamma \cdot \mu_0 \cdot \left\{ -H_0 + \frac{\partial \varphi}{\partial z} + \frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s} \cdot \left(-k^2 + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \right\} \cdot m_x + M_s \cdot \frac{\partial \varphi}{\partial x} \end{cases} \quad (8)$$

Next, we use the approximation of a uniform wave, for which the following conditions are met:

$$\begin{cases} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) m_y = 0 \\ \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) m_x = 0 \end{cases} \quad (9)$$

For a uniformly magnetized sample, if the magnetization fluctuations are significantly smaller compared to the initial magnetization, we also write down the conditions for the magnetostatic potential:

$$\frac{\partial \varphi}{\partial x} \approx 0, \quad \frac{\partial \varphi}{\partial y} \approx 0, \quad \frac{\partial \varphi}{\partial z} \approx 0 \quad (9a)$$

Equations (9) and (9a) are the final linearization conditions of equation (8). Finally, we find the final form of the linearized system of LLG equations for elongated samples:

$$\begin{cases} \frac{\partial m_x}{\partial t} = -m_y \cdot \gamma \cdot \mu_0 \cdot \left[H_0 + 2 \frac{A_{ex}}{\mu_0 \cdot M_s} \cdot k^2 \right] \\ \frac{\partial m_y}{\partial t} = m_x \cdot \gamma \cdot \mu_0 \cdot \left[H_0 + 2 \frac{A_{ex}}{\mu_0 \cdot M_s} \cdot k^2 \right] \end{cases}, \quad (10)$$

This system has an obvious solution in the form of periodic harmonic oscillations (the simplest possible solution):

$$\begin{cases} m_x(t, x, y) = -C \cdot \sin \left[\left(\gamma \cdot \mu_0 \cdot H_0 + 2 \cdot \frac{\gamma \cdot A_{ex}}{M_s} \cdot k^2 \right) \cdot t \right] \\ m_y(t, x, y) = C \cdot \cos \left[\left(\gamma \cdot \mu_0 \cdot H_0 + 2 \cdot \frac{\gamma \cdot A_{ex}}{M_s} \cdot k^2 \right) \cdot t \right] \end{cases} \quad (11)$$

These solutions have the structure of a plane wave, the wave vector of which is directed along the magnetization axis of the sample (Fig. 1).

The spin wave dispersion law, derived from solutions (11), has the following form:

$$\omega(k) = \gamma \cdot \mu_0 \cdot H_0 + 2 \cdot \frac{\gamma \cdot A_{ex}}{M_s} \cdot k^2 \quad (11a)$$

Then the simplified system is as follows:

$$\begin{cases} \frac{\partial m_x}{\partial t} = m_y \cdot \gamma \cdot \mu_0 \cdot \left[H_0 + 2 \frac{A_{ex}}{\mu_0 \cdot M_s} \cdot k^2 \right] \\ \frac{\partial m_y}{\partial t} = -m_x \cdot \gamma \cdot \mu_0 \cdot \left[H_0 + 2 \frac{A_{ex}}{\mu_0 \cdot M_s} \cdot k^2 \right] \end{cases}, \quad (7)$$

This system has an obvious solution in the form of

periodic harmonic oscillation (Fig. 1).

This coincides with the result obtained within the framework of the theory developed by Kallinikos and

Slavin [1], provided that $\frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s^2} \cdot k^2 \gg F_k$:

$$\omega(k) = \sqrt{\left(\gamma \cdot \mu_0 \cdot H_0 + \frac{2 \cdot \gamma \cdot A_{ex}}{M_s} \cdot k^2\right) \cdot \left[\gamma \cdot \mu_0 \cdot H_0 + \gamma \mu_0 M_s \cdot \left(\frac{2 \cdot A_{ex}}{\mu_0 \cdot M_s^2} \cdot k^2 + F_k\right)\right]}, \quad (12)$$

where F_k is the depolarization factor that determines the magnetostatic interaction.

For the propagation geometry defined above, when $\vec{k} || \vec{H}_0$ (Fig. 1), the value of $F_k = 1$. Using (12), we write the condition that determines the possibility of not taking into account the magnetostatic interaction more precisely:

$$k^2 \gg \frac{\mu_0 \cdot M_s^2}{2 \cdot A_{ex}}. \quad (13)$$

The obtained results make it possible to conclude that a uniform wave is one of the possible solutions that correctly describes the spin wave propagation process.

The corresponding values of k for which this is possible, calculated for different materials according to equation (13), are given in Table 2.

As can be seen from the data given in Table 2, exchange spin waves can be detected if the wavelength is tens of rad/μm, but such experimental conditions are usually difficult to implement, instead hybrid waves (magnetostatic and exchange) are detected, and the dispersion law differs from the theoretical dependences (11a) and (12). This is due, in particular, to the fact that exchange spin waves have a short wavelength and therefore require control at the nanoscale. However, their great advantage is that the dispersion law is practically not affected by the shape of the sample, which is a significant

factor for magnetostatic waves. This requires research technologies that differ from classical microwave technologies, an example of such research is described in detail in [7].

Using the dispersion expression (11a), condition (13), and data on the properties of the materials given in Table 2, we determine the value of the magnetic field at which exchange spin waves dominate.

These results are shown in Fig. 2, which shows the dependence of the frequency of spin waves on the applied magnetic field, calculated for the critical value of the wave vector (Table 2) of two magnetic substances: Py, YIG.

According to the data presented in Fig. 2, it can be concluded that for external magnetic field values from 20 to 200 mT, samples made with permola can be used in the range from 29 to 35 GHz, and yttrium garnet from 5 to 11 GHz. For practical use of the dispersion properties of exchange spin waves, it is necessary to control their properties at the submicrometer level, which is currently an unsolved problem. However, there are works that determine the prospects for the application of exchange spin waves in electronic devices for detecting electromagnetic waves. Other promising materials, the use of which makes it possible to control spin waves, are antiferromagnets, but their use requires compliance with nanometer sizes of structures formed by magnetic substances with parallel and antiparallel alignment.

Table 2.
Typical values of material characteristics, sample dimensions, and wave vector values

№	Material	Saturation magnetization, M_s , mT	Exchange stiffness constant, A_{ex} , pJ/m	Wave number, k rad/μm	Geometric dimensions	Source
1	YIG	110	3.85	44.5	250 nm × 340 nm × 100 μm	[2]
2	Py	800	10	268	80 nm × 80 nm × 200 μm	[17]

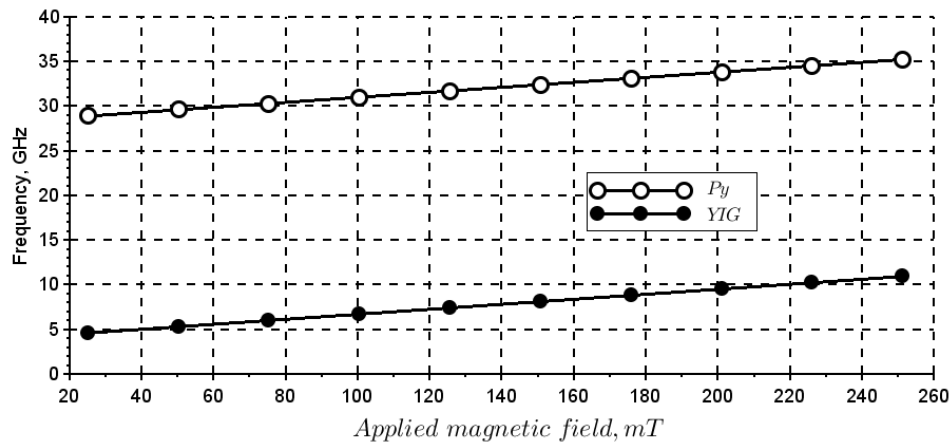


Fig. 2. Dependence of the frequency of detected spin waves on the applied magnetic field, calculated for the critical value of the wave vector (Table 2), of two magnetic substances: Py, YIG.

III. Discussion of results and conclusions

Using the expansion of the Landau-Lifshitz-Gilbert vector equation for a sample in the form of a rod magnetized along the long axis, taking into account the exchange interaction and neglecting the damping of magnetic precession, the dispersion relations of spin waves for samples made of polycrystalline magnetic material with uniform magnetization along the rod are determined. The obtained dispersion relations coincide with the results of the Kallinikos and Slavin model, which assumes a weak magnetostatic interaction. This situation is realized if the wavelength exceeds some critical value, which depends on the properties of the material (44 rad/ μm for YIG and 268 for Py). The obtained results are promising for spintronic devices in the microwave and millimeter ranges, which are expected to be used or are used in 5G and 6G communication technologies.

When discussing the applicability of the results obtained, we note two main points: 1) the choice of frequency range; 2) the choice of material. According to our calculations, exchange spin waves can occur in the microwave and millimeter frequency ranges for materials such as Py and YIG, but this requires measuring the properties of the waves on the submicron scale. Antiferromagnetic materials are also promising, which can provide operation in the higher frequency range.

This model has limitations, since the anisotropy factor and the interaction of spin waves with the lattice (spin-phonon interaction) are not taken into account. Therefore, further directions of theoretical research may be the search for solutions of the linearized LLG equation that take into account anisotropy. Taking into account the quantum effects of the interaction of spin waves with the lattice requires the use of a microscopic approach, in contrast to the classical macroscopic LLG model. Given the quantum nature of exchange waves, consideration of the damping process requires taking into account the specifics of the mechanisms of interaction of magnons (spin wave particles) with the material to refine the macrospin model, which uses a single damping parameter (since it is necessary to control processes on a submicron scale).

Conclusions

Using the linearized system of LLG equations, a dispersion relation for spin waves is obtained, which coincides with the well-known theoretical model of Kallinikos and Slavin. Based on this model, the possibility of the existence of a homogeneous spin wave, which coincides in its structure with a plane wave, is shown.

Author contributions

R. P. analyzed the sources on the research topic: properties and use of spin waves, problem formulation and construction of a mathematical model, analyzed the results obtained; M. V. analyzed the possibility of using spin waves, in particular in biomedical research; I. D. analyzed the sources on the research topic; I. K. constructed a mathematical model and solutions to the system of equations for magnetic moments, performed an analysis of potential ways to extend the model to more complex cases of magnetic potential; M. S. performing calculations and analyzing results; N. M. prepared the research results in the form of an article.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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У статті досліджуються дисперсійні властивості спінових хвиль шляхом лінеаризації рівняння LLG, яке застосовується для довгих зразків із поперечними розмірами нанометрового масштабу, у припущенні їх полікристалічної структури. Отриманий закон дисперсії в цілому збігається з результатом іншої відомої теоретичної моделі поширення спінових хвиль, а саме моделі Калінікоса-Славіна. Проаналізовано обмеження моделі, зумовлені такими припущеннями, як: відсутність затухання Гільберта та відсутність внутрішньої анізотропії (полікристалічність). Одержані кількісні характеристики для найбільш поширених у практичних застосуваннях магнітних матеріалів, на основі яких виділені потенційні діапазони частот, у яких переважає обмінна взаємодія, і у яких виявляється квадратичний закон дисперсії спінових хвиль. Отримані результати є перспективними для телекомунікаційних технологій майбутніх поколінь та біохімічних досліджень завдяки добре прогнозованим властивостям спінових хвиль та можливості мініатюризації пристроїв детектування електромагнітного випромінювання гігагерцового діапазону.

Ключові слова полікристалічні магнітні зразки, спінові хвилі, скалярний магнітний потенціал, однорідна хвиля, обмінна взаємодія.