Features of spin-wave envelope solitons of the terahertz frequency range in thin hexaferrite films

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Abstract. The paper is devoted to the study of the formation and propagation features of terahertz bright envelope solitons of dipole-exchange spin waves in thin ferrite and hexaferrite films. The influence of the exchange interaction and the uniaxial anisotropy field on the soliton formation threshold is studied.

1. Introduction

In recent years, the increase of development terahertz and sub-terahertz devices is observed in the electronics. For that reason, the investigation of the terahertz physics effects that can serve as a basis for the new devices is needed. The ferrites with the hexagonal crystal structure, so called hexaferrites, demonstrate unique waveguide properties in the 0.1-1 THz frequency range. The device operation frequency can be increased due to usage of the hexaferrites in the relatively low magnetic bias field. This is possible because the hexaferrites have the high effective fields of uniaxial magnetic crystallographic anisotropy [1].

From the radiophysics point of view, the ferrites and hexaferrites are nonlinear dispersive waveguide media. In this type of media stability wavepackets, namely envelope solitons can exist. The solitons are studied in the ferromagnetic films [2, 3], optical fibers [3], Bose-Einstein condensate [4], etc. In spite of that, the solitons are well investigated in the mentioned media, the features of bright spin-wave envelope solitons in thin hexaferrite films are not revealed.

It is well known, that the spin wave (SW) in ferrites can exist due to dipole-dipole and exchange interactions. The relative contribution of the each type of the interactions are different in the different wavenumber ranges. It is worth noting a paper [5] that is devoted to a soliton investigation in hexaferrite films, but there the solitons were studied in such wavenumber range where only dipole-dipole interaction contribute to the wave process. Thus, the influence of the exchange interaction on the formation and propagation soliton processes is not well studied.

The aim of this paper is to investigate theoretically the impact of the anisotropic properties and exchange interaction of the hexaferrite thin films on terahertz bright envelope solitons. Note that the investigation was carried out in the terahertz and sub-terahertz frequency ranges that can be significant for the applications.
2. Theoretical Investigation

The investigation in this paper was carried out in several steps. First, a dispersion characteristic of SW propagating in the hexaferrite thin film was evaluated. Second, coefficients of the nonlinear Schrodinger equation (NLSE) that described the soliton process were calculated. In the end, influence of the exchange interaction and the anisotropy on the threshold of soliton formation was analyzed.

In the investigation the BaFe$_{12}$O$_{19}$ M-type (BaM) hexaferrite thin film that was magnetized to saturation with the magnetization $M_0=4800$ Gs and the uniaxial anisotropy field $H_a=17000$ Oe was studied [1]. The film thickness was $L=5.6$ µm. The bias field had value $H_0=2000$ Oe and was orientated in the plane. The wave propagating along the bias field was investigated.

The dispersion characteristic based on the dispersion equation for dipole-exchange SW, which was obtained in [6], was evaluated numerically. The evaluation was fulfilled for two sets of parameters. The first set was mentioned above; it is the hexaferrite thin film. The second corresponds to an yttrium iron garnet (YIG) film that had the same parameters exclude the saturation magnetization and the anisotropy. The YIG film has the saturation magnetization $M_0=1750$ Gs and the cubic anisotropy field $H_a=70$ Oe. The obtained dispersion characteristic is plotted in Figure 1.

![Image of Figure 1](image_url)

**Figure 1.** The dispersion characteristic of SW. The solid line is BaM, the dash line is YIG, the gray dotted line shows wavenumber

It is obvious from the figure that the frequency range of the propagating SW in the hexaferrite BaM film lies above in compare with the waves in the ferrite YIG film due to the anisotropy. The exchange interaction differently impacts on the dispersion curve of SW in different films, the slope of the BaM curve starts at greater wavenumber than the slope of the YIG curve.

Hereafter the wavenumber of the propagating SW was fixed at $k_0=10^6$ rad/cm. This value is showed with the gray dotted line in the Figure 1. At the selected wavenumber, the frequency of the propagating SW in the hexaferrite equals 0.15 THz; the frequency of the SW in the ferrite equals 23 GHz.

It is well known that the propagating wave processes is described with the NLSE in the nonlinear, dispersion and dissipative media [2]:

$$i\left(\frac{\partial u}{\partial t}+V_x \frac{\partial u}{\partial z}\right)+\frac{D}{2} \frac{\partial^2 u}{\partial z^2} - N |u|^2 u = -i\Gamma u,$$

where $V_x = \bar{c} \omega / \bar{c} k$ is the group velocity, $D = \bar{c}^2 \omega / \bar{c} k^2$ is the dispersion coefficient, $N = \bar{c} \omega / \bar{c} |u|^2$ is the nonlinear coefficient, $\Gamma$ is the damping decrement. For the mentioned sets of the parameters these coefficients are following for the BaM film: $V_x = 8.3 \cdot 10^4$ cm/s, $D = 8.3 \cdot 10^{-2}$ cm$^2$/s, $N = -1.4 \cdot 10^{11}$ rad/s, for the YIG film $V_x = 3 \cdot 10^4$ cm/s, $D = 3 \cdot 10^{-2}$ cm$^2$/s, $N = -1.7 \cdot 10^{10}$ rad/s. The damping decrement was evaluated based on the results of the paper [1].

The soliton processes was analyzed with a numerical modeling of NLSE. The modeling results for the both films concluded that the exchange interaction lead to a reducing of the influence of dispersion
spreading effect on soliton processes. The compare of the modeling results for the films showed that the increasing of the anisotropy field results in an enhancement of the self-phase modulation effect.

Let us turn to description of the threshold of the bright spin-wave envelope solitons in the both films. The study was carried out with the formulae from the paper [7]. The formulae were modified taking into account the anisotropy and the exchange interaction. The investigation results are showed in the Figure 2. The plotted curves are described the relation between the threshold $|u_{th}|^2$ and an input pulse duration $\tau$, which is needed for the formation of the solitons.

![Figure 2. The bright soliton thresholds for several cases: (1) is for the BaM film, (2) is for the YIG film, (3) is for the BaM film without the exchange interaction, (4) is for the YIG film without the exchange interaction.](image)

One can infer two conclusions from the Figure 2. First, the increase of the anisotropy field leads to the increase of the threshold and the decrease the input pulse duration. Second, the exchange interaction significantly reduces the input pulse duration for which minimum threshold is observed both in the ferrite and hexaferrite films.

Let us give a comparison of the obtained results and results from work [5]. Note that the material parameters of the investigated hexaferrite and a hexaferrite from the work [5] are close. At the same time, carrier frequencies are distinguished drastically. It provides different physical background for soliton excitation because of in our work the carrier SW wavenumber is much higher than in work [5]. Such a high value corresponds to exchange spectrum of spin waves. Namely, in the work [5] the upper boundary of the soliton carrier frequency is 37.4 GHz and the duration of the single soliton at the generation threshold to be 2 ns. This frequency is much less than the soliton carrier frequency in our investigation that is 0.15 THz. As a result, we obtained twice-smaller duration of the single soliton. This was possible by taking into account the exchange interaction.

Acknowledgments

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