Investigation of Frequency-Angular Dependences for Surface Magnetostatic Spin Waves in Cubic Ferrite Films

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Abstract – Investigation of behavior of surface magnetostatic spin waves (SMSW) propagating in thin ferrite films, in particular yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$), are very important because of their use in spin-wave electronic devices. In this work, we have studied frequency-angular dependences of SMSW in cubic ferrite films. To analyse these dependences we use a proposed method of obtaining an approximate dispersion equation for SMSW in a weakly anisotropic ferromagnetic film. The derived equation provides an explicit analytic description of the wave frequency on the tensor components of effective demagnetizing anisotropy factors. It has been shown that for films with orientations {100} and {110} the angular dependencies of frequencies were the most significant. For the films with the {111} orientation, the angular dependencies were the weakest. Also, we have obtained the angular dependencies of the SMSW frequencies in {110}-films with both cubic and uniaxial anisotropy. The results can be used for both improving the characteristics of ferromagnetic films and development of spin-wave devices.

1. Introduction

Use of surface magnetostatic waves (SMSW), excited in thin ferrite films, allows to solve a number of problems on processing signals in a range of frequencies from 0.5 up to 20 GHz. Investigation of frequency-angular dependences of SMSW in cubic ferrite films is playing an important role in the development of spin-wave devices. The purpose of this paper was to obtain these dependences.

The objects of our investigation were films with a cubic magnetic anisotropy, which are oriented along the planes passing through axis of the <110> type. It should be noted in connection with the problem being considered that the basic material used in spin-wave electronics is yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$) belonging to weakly anisotropic ferrites with a cubic symmetry of the crystal lattice. Films with crystallographic orientations of the {111} type have found the widest application. The results of analysis of anisotropy in the SMSW spectrum in YIG films with the {111} orientation are given in [1]. At the same time, some characteristics of spin-wave devices can be improved by using films with other orientations. In particular, it was noted in [2, 3] that the thermal stability of the SMSW spectra for films with the {110} and {100} orientations is higher than for {111} films. All these orientations ({111}, {110}, and {100}) are particular cases of the model under investigation.

2. Results and discussion

In [4] it has been obtained approximated dispersion equation provided an explicit analytic description of the wave frequency f on the tensor components N_{ij}^a of effective demagnetizing anisotropy factors. We use the dispersion equation for studying the angular dependences of frequency in tangentially magnetized films of cubically anisotropic ferrites.

You can see this equation (1) below:

$$f^2 = f_0^2 \exp(-2kd) + f_\infty^2 \left[1-\exp(-2kd)\right] - P(kd)\sigma - R(kd)\varepsilon, \quad (1)$$

where

$$P(kd) = \left\{\left[\exp(-2kd)\right]/2\right\}\left\{2kd/\left[1-\exp(-2kd)\right]-1\right\},$$

$$R(kd) = \left[\exp(2kd)-1\right]^{-1} \times \left\{4kd/\left[1-\exp(-2kd)\right]+\exp(-2kd)-3\right\},$$

$$\sigma = 4\pi\left(M_0 g\right)^2\left(N_{xx}^a - N_{yy}^a\right),\ \ \varepsilon = \left(M_0 g N_{xx}^a\right)^2.$$

In equation (1) f_0, f_∞ are the boundary frequencies of the spectrum of magnetostatic spin waves; k is wave vector; d is the thickness of ferromagnetic film; g is gyromagnetic ratio.

Figure 1 illustrates the model for a film with the tangential {110} axis. The crystallographic orientation of the magnetization vector is specified with two angles: angle ψ measured from the <110> axis in the plane of the film and angle δ defining the inclination of the {100} plane passing through the <110> axis under consideration to the plane of the film. Cubic anisotropy will be taken into account using only one constant. Films with the {111} orientation will be considered separately, since two constants must be taken into account for such films.

The components of tensor N_{ij}^a appearing in the dispersion equation are described by the expressions (these expressions are derived, analogously to [1], on the basis of the formulas connecting components N_{ij}^{a} with the cosines of the angles between the coordinate axes in system *XYZ* and the axes [100], [010], and [001] of the cubic crystal).

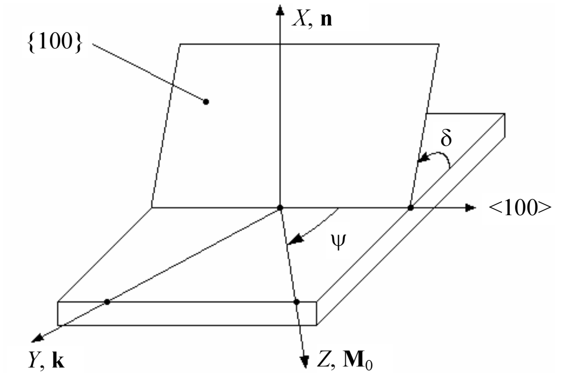

Fig. 1. Model of a ferromagnetic film

$$\left.\begin{aligned}
&M_0 N_{xx}^{c(1)} = (-2K_1^c / M_0)\{1-[(1+3\cos 2\delta)/16]\times \\
&\times[(1+3\cos 2\delta)+3(1-\cos 2\delta)\cos 2\psi]\},\\
&M_0 N_{yy}^{c(1)} = (-K_1^c / M_0)\{1+[(1+3\cos 2\delta)/32]\times \\
&\times[(1+3\cos 2\delta)+3(5-\cos 2\delta)\cos 4\psi]\},\\
&M_0 N_{zz}^{c(1)} = (-K_1^c / M_0)\{1+[(1+3\cos 2\delta)/32]\times \\
&\times[(1+3\cos 2\delta)+4(1-\cos 2\delta)\cos 2\psi - \\
&-(5-\cos 2\delta)\cos 4\psi]\},\\
&M_0 N_{xy}^{c(1)} = (3K_1^c \sin 2\delta / M_0)\{\cos 3\psi + \\
&+[(1+3\cos 2\delta)/8]+(\cos\psi - \cos 3\psi)\},
\end{aligned}\right\} \quad (2)$$

where K_1^c is the first constant of cubic magnetic anisotropy.

Figure 2 shows examples of the angular dependences of the SMSW frequencies calculated using Eq. (1) with substitution of expressions (2).

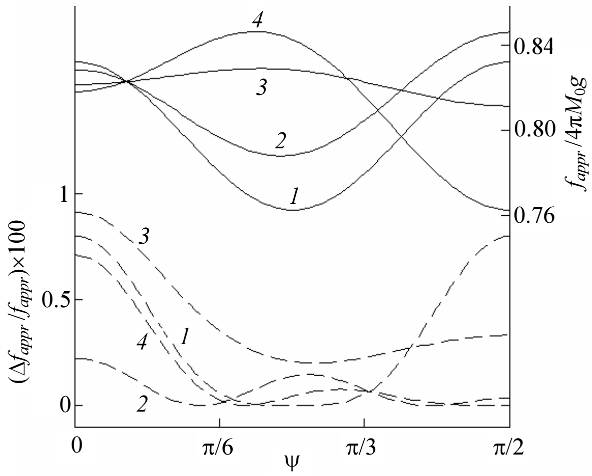

Fig. 2. Angular dependences of the SMSW frequency for $kd = 1$ in a cubic anisotropic film

It has been used the values of magnetic parameters of YIG crystal ($4\pi M_0 = 1750$ G, $K_1^c / M_0 = -43$ Oe, and $H_e/4\pi M_0 = 1/3$). Figures on the curve correspond to the following values of angle δ: 0 (*1*), π/6 (*2*), π/3 (*3*), and π/2 (*4*). Dependences $f_{appr}(\psi)$ are calculated using approximate dispersion equation (1) (solid curves). In calculating errors (dashed curves), we used the dependences $f(\psi)$ derived from exact equation [2] as well as the differences $\Delta f_{appr} = f_{appr} - f$ and $\Delta f = \max\{f(\psi)\} - \min\{f(\psi)\}$. Additional analysis of calculated data revealed that the largest difference between exact and approximate dispersion equation (DE) is manifested in the vicinity of $kd = 1$. In Figure 2, this difference does not exceed 1% relative to angular variations of frequency associated with the effect of cubic anisotropy (i.e., relative to the difference $\max\{f(\psi)\} - \min\{f(\psi)\}$).

The following two peculiarities are worth noting. The first corresponds to films with orientations {100} and {110} (δ = 0 and δ = π/2). For these orientations, the angular dependence of frequencies is the most significant. Nevertheless, the approximate DE describes this dependence to a high degree of accuracy. The second peculiarity concerns films with the {111} orientation. In this case, $(1 + 3\cos 2\delta) = 0$ and, in accordance with relations (2), the dependence on angle ψ is observed only for component $N_{xy}^{c(1)}$. In contrast to diagonal components, N_{xy}^{a} appears in the DE in quadratic form; for this reason, the angular dependence associated with this component is the weakest. In this case, as shown in [1], the analysis of anisotropy of the SMSW spectrum requires the inclusion of not only the first, but also the second, constant of cubic magnetic anisotropy. The tensor components of effective demagnetizing factors corresponding to the inclusion of the second constant (K_2^c) have the following form (the expressions were derived in the same way as expressions (1)):

$$M_0 N_{xx}^{c(2)} = K_2^c / 6M_0,$$

$$M_0 N_{yy}^{c(2)} = \left(K_2^c / 18M_0\right)\left(1+5\cos 6\psi\right),$$

$$M_0 N_{zz}^{c(2)} = \left(K_2^c / 18M_0\right)\left(1-\cos 6\psi\right),$$

$$M_0 N_{xy}^{c(2)} = \sqrt{2}K_2^c \cos 3\psi / 6M_0.$$

The results shown in Fig. 3 visually demonstrate the effect of the second constant on the angular dependence of the SMSW frequencies in {111} films. In Fig. 3 solid and dashed curves are calculated using approximate and exact dispersion equations respectively. The values of magnetic parameters are the same as in Fig. 2. Curves *1* take into account only the first anisotropy constant, while curves *2* account for the first aild the second anisotropy constants (the latter was taken as $K_2^c / M_0 = -2$ Oe). It should be noted that the approximate DE successfully describes the “amplitude” and “phase” of angular variations of frequencies.

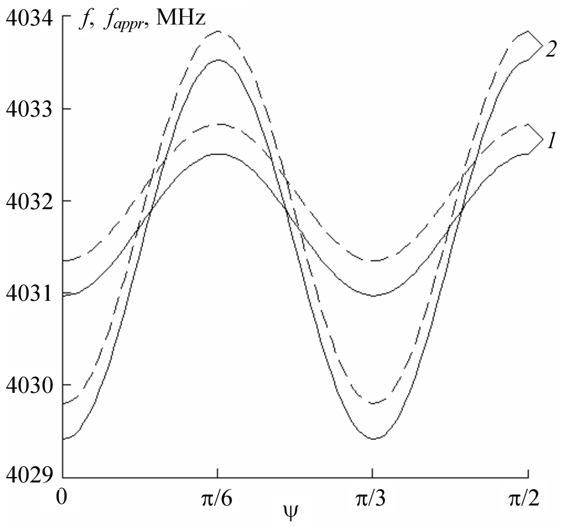

Fig. 3. Angular dependences of the SMSW frequency for $kd = 1$ in a film of a cubic crystal with the {111} orientation

Let us introduce into the film model the uniaxial anisotropy in addition to cubic anisotropy. For example, both types of anisotropy can be present in YIG films [5]. We will assume that the principal axis of uniaxial anisotropy is directed along the normal to the film. Then, in the geometry of tangential magnetization, the tensor components of the effective demagnetizing factors of uniaxial anisotropy have the form

$$M_0 N_{xx}^u = -2K_1^u / M_0,$$

$$N_{yy}^u = N_{zz}^u = N_{xy}^u = 0, \qquad (3)$$

where K_1^u is the first uniaxial anisotropy constant.

Examples of the dependences calculated on the basis of expressions (2) and (3) are given in Fig. 4. The film orientation is {110} ($\delta = \pi/2$). Dependences $f_{appr}(\psi)$ are calculated using approximate DE (1) (solid curves), while the $f(\psi)$ dependences are based on exact DE [2]. The dashed curves describe the difference $f_{appr}(\psi) - f(\psi)$. The magnetic parameters are the same as in Fig. 2. The figures on the curves correspond to the following values of the uniaxial anisotropy constant: $K_1^u = 0$ (*1*); $K_1^u = K_1^c$ (*2*), and $K_1^u = -K_1^c$ (*3*).

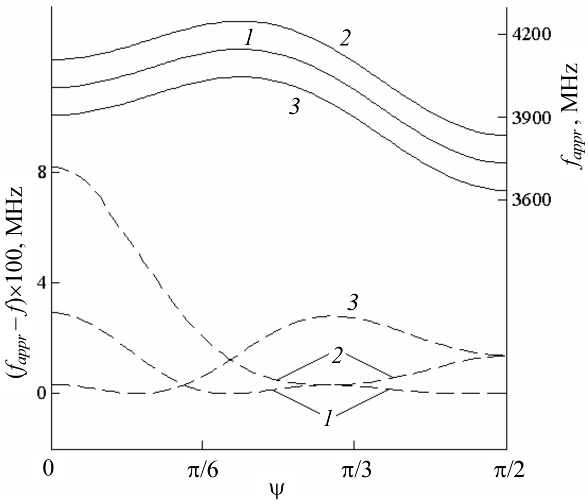

Fig. 4. Angular dependences of the SMSW frequency for $kd = 1$ in a film with cubic and uniaxial anisotropy

The approximate DE derived here takes into account magnetic anisotropy in the most general form and, hence, can be applied for monocrystalline ferromagnetic films with any type of the crystal lattice and with an arbitrary crystallographic orientation. The simple analytic form of the approximate DE makes it possible to substantially simplify analysis of the process occurring in anisotropic films with the participation of SMSWs.

Thus, our results can be used for improving the characteristics of ferromagnetic films and in development of spin-wave devices.

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