Influence of Magnetocrystalline Anisotropy on Thermostability of Magnetostatic Backward Volume Waves Characteristics in Cubic Ferrite Films

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Abstract – The purpose of the paper was to develop a method for the thermal stabilization of the frequency of backward volume magnetostatic waves (BVMSWs) in a tangentially magnetized cubic ferrite film. The proposed method is based on the dependence of the temperature coefficient of frequency on the magnetizing field orientation relative to the crystallographic axes of the film. Possibilities of the new method are demonstrated for the iron yttrium garnet films, the properties of which allow the thermal stability of frequency-selective MSW devices to be significantly improved. In addition, by properly selecting the crystallographic orientation of the film surface and the magnetization direction, it is possible to provide for the mutual compensation of both positive and negative variations of the parameters of other elements of MSW devices.

1. Introduction

Ion implantation of cubic ferrite films is good mean for effective operation of magnetostatic waves (MSV) characteristics. Formation of a layer with damage structure leads to change of magnetic parameters. Usually profiles of one-axie magnetic anisotropy are investigated. However cubic films have perfect crystalline structure and connected with it a field of magnetic anisotropy. The effect of magnetocrystalline anisotropy on thermostability of magnetostatic waves in ferrite films has been studied in the past[1,2], however, the investigations has been restricted to the case of $\mathbf{k} \perp \mathbf{M}$ (where $\boldsymbol{k}$ is the wave vector and $\boldsymbol{M}$ is the static magnetization vector). The purpose of this study was to develop a method for the thermal stabilization of the magnetostatic backward volume waves (MSBVW) in a tangentially magnetized cubic ferrite film when $\boldsymbol{k} \parallel \boldsymbol{M}$.

2. Results and discussion

It was assumed that the film size allows the effect of demagnetizing field on the temperature-induced frequency variations of BVMSWs to be ignored. According to [3], the temperature- compensating effect of the demagnetizing field is pronounced when the ratio of film thickness to lateral size in the magnetization direction is greater than 0.1. When this ratio is on the order of 0.01, the temperature-induced frequency shift is close to the values characteristic of a film with infinite lateral dimensions.

The proposed method is based on the dependence of the temperature coefficient of frequency (TCF) on the magnetizing field orientation relative to the crystallographic axes of the film.

The main source of thermal instability of the MSW characteristics is the temperature dependence of the saturation magnetization of ferrite. At first glance, it appears that the proposed method can be realized only in strongly anisotropic materials where the magnetic anisotropy field is on the same order of magnitude as the saturation magnetization. However, at present, the main material for the spin-wave electronics is yttrium iron garnet (YIG) belonging to weakly anisotropic ferrites. Possibilities of the new method will be demonstrated in application to the YIG films.

Let us consider the factors influencing the temperature-induced shift of the BVMSW frequency in anisotropic ferrite films. In constructing a theoretical model, we will proceed from the dispersion equation in a zero-exchange approximation derived in a traditional way [4]. In the case of $\mathbf{M} \perp \mathbf{n}$ and $\mathbf{k} \parallel \mathbf{M}$, where $\mathbf{M}$ is the magnetization vector, $\mathbf{n}$ is the film normal, and k is the wave vector, the MSW dispersion equation can be written as [5]

$$\tan\left(\frac{kd}{\sqrt{-\mu_{xx}}}\right) = \frac{2\sqrt{-\mu_{xx}}}{1+\mu_{xx}} \qquad (1)$$

where d is the film thickness and μ_{xx} is the magnetic permeability tensor component in the coordinate system (x, y, z) with the axes $x \parallel \mathbf{n}$ and $z \parallel \mathbf{M}$. The latter quantity is given by the formula:

$$\mu_{xx} = \frac{f_1^2 - f^2}{f_s^2 - f^2} \qquad (2)$$

where ŕ is the variable frequency, $ŕ_1$ and $ŕ_s$ are the longwave and shortwave boundary frequencies of the BVMSW spectrum

$(f_l/g)^2 = [H_z + M(N^c_{yy} - N^c_{zz})] \cdot [H_z + M(N^c_{xx} - N^c_{zz}) + 4\pi M - H_u] - (MN_{xy})^2,$

$(f_s/g)^2 = [H_z + M(N^c_{yy} - N^c_{zz})] \times [H_z + M(N^C_{XX} - Nl_z) - H_u] - (MN_{xy})^2,$

$g = 2.8$ MHz/Oe is the gyromagnetic ratio, H_z is the projection of the external magnetic field onto the direction of vector **M**, N^c_{ij} are the effective demagnetizing factors of the crystallographic magnetic anisotropy, $H_u = 2K_u/M$ is the uniaxial normal anisotropy field with the first constant K_u [4], and $4\pi M$ is the saturation magnetization of the ferrite crystal.

Let us simplify description of the crystallographic orientation of **M** by considering the magnetization directions coinciding with the third- and fourth-order symmetry axes of the ferrite crystal. In this context, further analysis refers to the films of cubic ferrites with a surface oriented in the {110} direction. In this case, the film plane contains the symmetry axes <111> and <100>. The effective demagnetizing factors for these directions are described by the relationships

$$M(N^c_{xx} - N^c_{zz}) = M(N^c_{yy} - N^c_{zz}) = H_c N_{\langle pqr\rangle},$$
$$N_{xy} = 0,$$

where $H_c = K_c/M$ is the cubic anisotropy field with the first constant K_c , $N_{<111>} = -4/3$, and $N_{<100>} = 2$; note also that $H_z = H$.

An expression for the temperature derivative df/dT can be obtained from formulas (1) and (2), taking into account that kd = const and, hence, $d\mu_{xx}/dT = 0$. After simple transformations, we obtain the following expression for the TCF:

$$\alpha \equiv \frac{1}{f}\frac{df}{dT} = \frac{1}{2}\left[\left(1 - \frac{g^2 H_{in}^2}{f^2}\right)\frac{1}{4\pi M}\frac{d(4\pi M)}{dT} + \left(1 + \frac{g^2 H_{in}^2}{f^2}\right)\frac{N_{\langle pqr\rangle}}{H_{in}}\frac{dH_c}{dT} - \frac{4\pi M H_{in} g^2}{f^2}\frac{d(H_u/4\pi M)}{dT}\right], \quad (3)$$

where $H_{in} = H + N_{<pqr>}H_c$ is the internal effective field strength.

Figure 1 shows the plots of $\alpha(f\text{K})$ and $kd(f)$ calculated using the parameters of YIG single crystals [6,7]. Note that the effect of the crystallographic magnetic anisotropy on the TCF is related both the product $N_{<pqr>}H_c$ and to the temperature derivative. The contribution to a due to the term $N_{<pqr>}dH_c/dT$ increases with decreasing H_{in}. From this it follows, in particular, that the difference between $\alpha_{<111>}$ and $\alpha_{<100>}$ (the subscript refers to the orientation of **M**) increases with decreasing magnetization field strength. This feature is confirmed by analysis of the data in Fig. 1.

The most interesting situation takes place for $\alpha_{<111>}$ and $\alpha_{<100>}$ possessing the opposite signs. In this case, there is a "thermostable" crystallographic direction between the tangent axes <111> and <100>, for which $df/dT = 0$. It should be noted that we assume a continuous dependence of α on the angles determining the orientation of vector **M**. An analysis based on the laws of dispersion describing the general case with an arbitrary crystallographic orientation of **M** [8,9] confirms the absence of discontinuities in the angular dependence of α. Using the method described in [8], it is also possible to calculate the external field **H** proceeding from the given "thermostable" direction **M** and the internal field strength.

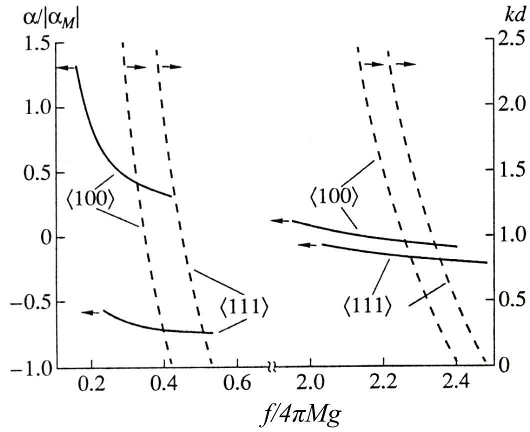

Fig. 1. The temperature coefficient of frequency (solid curves) and the principal mode dispersion (dashed curves) of BVMSWs in ferrite films calculated for $4\pi M = 1750$ G, $H_c = -42$ Oe, $d(4\pi M/dT = -4.0$ G/K, and $dH_c/dT = 0.4$ Oe/K; $a_M = (1/4\pi M)[d(4\pi M)/dT]$; magnetization directions indicated at the curves

Let us analyze the signs of $\alpha_{<111>}$ and $\alpha_{<100>}$. For YIG, the condition $\alpha_{<111>} < 0$ is valid for any H in the entire frequency spectrum of BVMSW frequencies. On the contrary, the condition $\alpha_{<100>} \geq 0$ leads to restrictions with respect to H and f values. In particular, the TCF values will be nonnegative in the entire BVMSW frequency spectrum provided that the minimum $a_{<100>}$ value attained at the longwave boundary $(f = f_l)$ is non-negative:

$$(df_l/dT)_{<100>} \geq 0$$

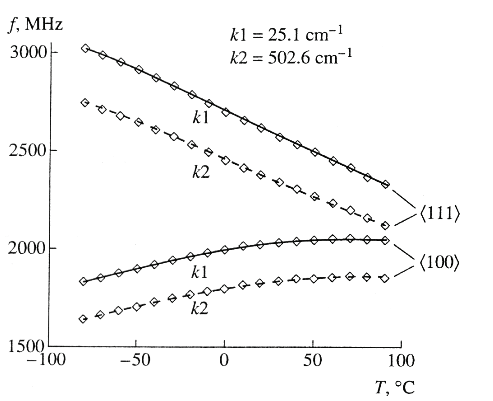

Fig. 2. Experimental plots of the principal mode frequency versus temperature for BVMSWs with two wave vectors in a YIG film magnetized along the tangent axes <111> and <100> in the externa] magnetic field with a strength of $H = 350$ Oe

Using the expressions derived above and accomplishing the necessary transformations, we obtain

$$H \leq H_0,$$

$$H_0 = -2\left[\frac{4\pi M_{\text{eff}}(dH_c/dT)}{d(4\pi M_{\text{eff}})/dT + 4(dH_c/dT)} + H_c\right],$$

$$4\pi M_{\text{eff}} = 4\pi M - H_u.$$

Thus, the theoretical analysis predicts the existence of a threshold field strength $H = H_0$ below which $\alpha_{<100>}$ is positive in the entire BVMSW frequency spectrum $(f_s < f \leq f_l)$. In particular, for YIG this value is $H_0 \approx 670$ Oe. The experiments were performed with a 10.6-μm-thick YIG film possessing the lateral dimensions 15 x 15 mm grown on a gadolinium gallium garnet substrate oriented in the <110> direction.

Note that the ratio of film thickness to lateral size is two orders of magnitude smaller than the value [3] for which the demagnetizing field effect is significant.

The results of measurements are presented in Fig. 2. The character of the experimental curves is consistent with the concepts developed above: the sign of TCF exhibits inversion in a small magnetization field, when the field orientation changes between the tangent axes <111> and <100>.

Using the properties of ferrite films described above, it is possible to improve the thermal stability of frequency-selective MSW devices. In addition, by properly selecting the crystallographic orientation of the film surface and the magnetization direction, it is possible to provide for the mutual compensation of both positive and negative variations of the parameters of other elements of MSW devices.

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