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MAGNETOSTATIC WAVES IN STRUCTURE WITH TWO ANISOTROPIC LAYERS WITH NONCOLLINEAR ORIENTATION OF MAGNETIZATIONS

A.F. Bukhanko
Donetsk Physicotechnical Institute NAS of Ukraine
R. Luxemburg str. 72, 83114, Donetsk, Ukraine
e-mail: buhanko@mail.fti.ac.donetsk.ua
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In this paper we present a theoretical investigation of the magnetostatic volume wave propagation in bilayer structure consisted of two ferromagnetic layers. The magnetic anisotropy field is assumed to be different in the two layers, and hence the magnetization in one layer can be aligned at an angle with respect to the magnetization direction in the other layer. The case of cubic and indused uniaxial anisotropy have been considered. Numerical calculations for YIG (yttrium-iron-garnet) ferrites show anisotropic propagation of the volume magnetostatic wave in that structure. Dispersion curves for YIG bilayer structure are shown to illustrate the effects of angle between the magnetization vectors in the magnetic layers and propagation direction on the properties of magnetostatic waves.
KEY WORDS: magnetostatic waves, bilayer structure, noncollinear orientation, anisotropy, dispersion relationship.

МАГНИТОСТАТИЧЕСКИЕ ВОЛНЫ В СТРУКТУРЕ С ДВУМЯ АНИЗОТРОПНЫМИ СЛОЯМИ С НЕКОЛЛИНЕАРНОЙ ОРИЕНТАЦИЕЙ НАМАГНИЧЕННОСТЕЙ

А.Ф. Буханько
Донецкий физико-технический институт НАН Украины
ул. Р.Люксембург 72., 83114, Донецк, Украина
В этой статье представлено теоретическое исследование распространения магнитостатических объемных волн в двухслойной структуре, состоящей из двух ферромагнитных слоев. Предполагается, что поле магнитной анизотропии в этих слоях различно и следовательно намагниченность в одном слое может быть неколлинеарна намагниченности в другом слое. Рассмотрен случай кубической и индуцированной одноосной анизотропии. Численный расчет для ЖИГ (железо-иттриевый гранат) показал, что распространение магнитостатических объемных волн в данной структуре является анизотропным. Для иллюстрации влияния угла между векторами намагниченности магнитных слоев и направления распространения на свойства магнитостатических волн приведены дисперсионные кривые для двухслойной ЖИГ структуры.
КЛЮЧЕВЫЕ СЛОВА: магнитостатические волны, двухслойная структура, неколлинеарная ориентация, анизотропия, дисперсионное соотношение.

МАГНИТОСТАТИЧНІ ХВИЛІ У СТРУКТУРІ З ДВОМА АНІЗОТРОПНИМИ ШАРАМИ З НЕКОЛІНЕАРНОЮ ОРІЄНТАЦІЄЮ НАМАГНІЧЕНОСТЕЙ

А.Ф. Буханько
Донецький фізико-технічний інститут НАН України
вул. Р. Люксембург 72, 83114, Донецьк, Україна
У цій статті представлено теоретичне дослідження поширення магнітостатичних об′ємних хвиль в двошаровій структурі, що складається з двох феромагнітних шарів. Передбачається, що поле магнітної анізотропії в цих шарах різне і отже намагніченість в одному шарі може бути неколінеарна намагніченості в іншому шарі. Розглянутий випадок кубічної та індукованої одновісної анізотропії. Чисельний розрахунок для ЗІГ(залізо-ітрієвий гранат) показав, що поширення магнітостатичних об′ємних хвиль в даній структурі є анізотропним. Для ілюстрації впливу кута між векторами намагніченості магнітних шарів і напряму поширення на властивості магнітостатичних хвиль приведені дисперсійні криві для двошарової ЗІГ структури.
КЛЮЧОВІ СЛОВА: магнитостатичні хвилі, двохшарова структура, неколінеарна орієнтація, анізотропія, дисперсійне співвідношення.

Over the last years the magnetostatic waves have attracted extensive attention on both theoretical and experimental aspects. Their phase velocity is small compared to the speed of light and so in describing magnetostatic waves we can use the equations of magnetostatics. If we take wave vectors in the region 30 cm^{-1}< $|k|$ < 10^5 cm^{-1} the dispersion relationship can be derived without taking exchange interactions and electromagnetic retardation into consideration.

Magnetostatic waves have been studied at first by Damon and Eshbach [1]. These waves are separated into three categories: magnetostatic surface waves (MSSW's) and magnetostatic backward-volume waves (MSBVW's) for the in-plane-magnetized film case and magnetostatic forward-volume waves (MSFVW's) for the perpendicularly magnetized film case. It should be pointed out that the exchange effects are not very important for backward-volume waves.

Increased interest in multilayer structures with noncollinear orientation of magnetization vectors associated with the fact that the external magnetic field applied in the plane of a film allows characteristics of the system to be easily changed by varying the angle between the magnetization vectors in the layers [2]. From the application point of view, having a bilayer with noncollinear orientation of magnetization vectors instead of a single film offers more degrees of freedom for tailoring special properties. Moderately simple and proficient control of properties magnetostatic modes in that structure by means of applying an external magnetic field open up fresh opportunities for their practical implementations.

A deficiency of magnetic or nonmagnetic ions in YIG can give rise to anisotropic terms different from cubic symmetry. The authors [3] found for YIG disks that can be uniaxial in-plane induced magnetic anisotropy as a result of the lattice mismatch. Also, the Bi-doped YIG film have strong induced magnetic anisotropy. For Bi-doped YIG, by controlling the factors affecting the induced magnetic anisotropy one can make the easy axis be either perpendicular or parallel to the structure.

Various authors have considered the influence of anisotropy on magnetostatic waves [4-7]. A substantial amount of work has been devoted to the analysis of magnetostatic waves in multilayers composed of ferromagnetic materials and dielectrics [8-12]. In [7] the theory is developed for dispersion characteristics of spin waves in ferromagnetic films taking into account both dipole-dipole and exchange interactions, crystallographic anisotropy and mixed exchange boundary conditions on the film surfaces.

So far as we know for the investigation of the magnetostatic waves such geometry of structure was employed only by Sun K and Vittoria S. [6]. In [6] the spectrum of MSSW has been studied for structure with noncollinear orientation of magnetizations $(M_1 \neq M_2)$ but no consideration has been given to volume magnetostatic waves.

We now consider this problem for the volume magnetostatic waves. The purpose of this paper is to investigate the effect of anisotropy on magnetostatic wave propagation in the layered structures with noncollinear orientation of magnetization vectors. As will be seen, these effect is of more interest in the case of the noncollinear magnetizations as compared to the parallel one. Our investigation have been restricted to the case of magnetization in the plane of the slab.

MODEL AND METHOD

Let us consider the magnetic structure consisting of two ferromagnetic films separated by a nonmagnetic interlayer (Fig.1), where equilibrium orientation of the magnetization vectors in the magnetic layers is supposed to be in the film plane and make a certain angle γ between each other. The film is assumed to be magnetically anisotropic. An external static magnetic field **H** is applied in the film plane at an angle Θ relative to the **X** -axis so that the total internal magnetic fields also lie in the planes of the layers. For simplicity assume that thicknesses of the ferromagnetic layers $d_1 = d_2$. Fig. 1 shows a bilayer structure placed in **X-Y-Z** coordinate system so that the plane of the film coincides with the **X-Y** plane. The vector **k** and angle φ designate the in-plane wave vector and propagation angle, respectively.

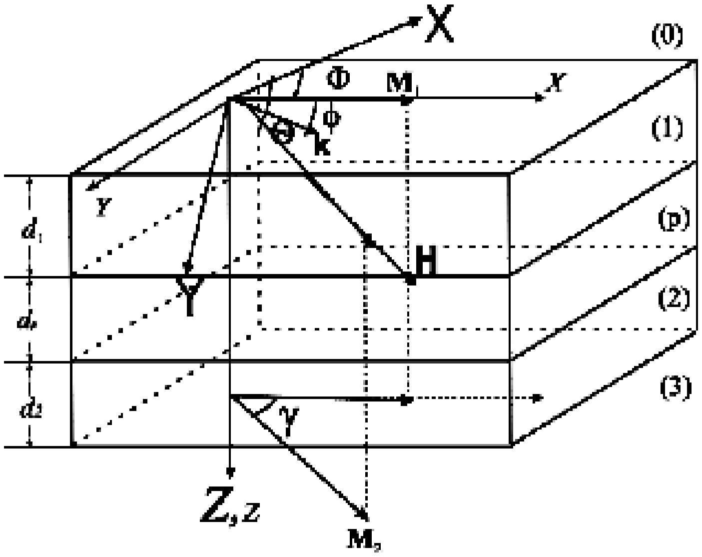


Fig.1. Film, field and magnetizations geometry.

For YIG the **X-,Y,Z-** axes represent the crystallographic directions for the cubic single crystal.

We make the simplifying assumptions that the film is infinite in the **X**- and **Y**-directions and has a thickness *d* in the **Z**-direction. An additional *x-y-z* coordinate system is also shown (the *x*-axis is along the $\mathbf{M}_1$ vector).

The saturation magnetization vector $\mathbf{M}_2$ coincides with vector **H** and the saturation magnetization vector $\mathbf{M}_1$ is at some angle *Φ* relative to the **X**-axis. The internal fields $H_o^{(1)}$ and $H_o^{(2)}$ also lie in the plane **X-Y**. The quantities $\mathrm{H}_o^{(1)}$ and $\mathrm{H}_o^{(2)}$ can be expressed in terms of the external field H, the static cubic anisotropy field components $H_A^{(1)}$ and $H_A^{(2)}$, and the static-induced in-plane anisotropy field component $\mathrm{H}_U^{(1)}$, where the superscripts (l) and (2) denote the layers corresponding to $\mathbf{M}_1$ and $\mathbf{M}_2$.

We use the macroscopic phenomenological theory: Maxwell's equations, considering the boundary conditions of the structure and the Landau-Lifshitz equation of motion for the magnetization. The macroscopic approach treats the total energy in terms of the magnetization. The magnetostatic dispersion relationship may be expressed in terms of permeability tensor elements for each rnagnetic layer.

The Landau-Lifshitz equation of motion for the magnetization of film *i* (*i*=1,2) is written as

$$\frac{d}{dt}\mathbf{M}_{(i)} = \gamma\left[\mathbf{M}^{(i)} \times \mathbf{H}_o^{(i)}\right] \quad (i = 1,2),$$
$$\mathbf{H}_o^{(i)} = -\left(e_x \frac{\partial F}{\partial \mathrm{M}_x^{(i)}} + e_y \frac{\partial F}{\partial \mathrm{M}_y^{(i)}} + e_z \frac{\partial F}{\partial \mathrm{M}_z^{(i)}}\right) \qquad (1)$$
$$F = F_A - \mathbf{M}\left(\mathbf{H} + \mathbf{h}\right)$$

where F_A - magnetocrystalline anisotropy free energy density, $\mathbf{H_o}$ – total internal field, **H -** external static magnetic field.

An magnetocrystalline anisotropy free energy density is written as

$$F_A = K_U\left(1 - \mathbf{M}_X^2 / \mathbf{M}_Y^2\right) + K_1\left(\mathbf{M}_X^2\mathbf{M}_Y^2 + \mathbf{M}_Y^2\mathbf{M}_Z^2 + \mathbf{M}_Z^2\mathbf{M}_X^2\right) \qquad (2)$$

where K_U denotes a uniaxial anisotropy energy density parameter, K_1 denotes a first order cubic anisotropy energy density parameter.

The internal $\mathbf{H}_o^{(i)}$ consists of the static effective field $\mathbf{H_s}$ and dynamic effective field **h** components, that contain anisotropy terms in the dynamic response for magnetostatic waves. Also, the magnetization is written as the sum of a static part **M** and a fluctuating part **m**. For layer (1), in the small signal limit in which $|m(r,t)| << M_s$ (M_s – saturation magnetization) is satisfied, m has only transverse components m_y and m_Z.

In order to obtain the magnetostatic dispersion relations, one has to find the permeability tensor elements for each layer.

By linearizing the Landau-Lifshitz equation (1), after some algebraic manipulations, the dynamic permeability tensors are obtained. For layer (1), where the lowest order terms in a small amplitude dynamic response involve only the *y*- and *z*- components of the total magnetization vector $\mathbf{M}^{(1)}$, it is given by

$$\begin{pmatrix} b_y \\ b_z \end{pmatrix} = \hat{\boldsymbol{\mu}}\begin{pmatrix} h_y \\ h_z \end{pmatrix} = \begin{pmatrix} 1 + k_\alpha & -i\nu \\ i\nu & 1 + k_\beta \end{pmatrix}\begin{pmatrix} h_y \\ h_z \end{pmatrix}$$

$$k_\alpha = \frac{\Omega_\alpha}{\Omega_\alpha\Omega_\beta - \Omega^2}, \quad k_\beta = \frac{\Omega_\beta}{\Omega_\alpha\Omega_\beta - \Omega^2}, \quad \nu = \frac{\Omega}{\Omega_\alpha\Omega_\beta - \Omega^2} \qquad (3)$$

$$\Omega = \frac{\omega/\gamma}{4\pi M_s}, \quad \Omega_{\alpha,\beta} = \frac{H_{\alpha,\beta}}{4\pi M_s}$$

where

$$H_\alpha = H\cos\left(\Theta - \Phi\right) + H_U\cos^2\left(\Phi\right) + H_A\left[1 - \frac{\sin^2\left(2\Phi\right)}{2}\right]$$
$$H_\beta = H\cos\left(\Theta - \Phi\right) + H_U\cos\left(2\Phi\right) + H_A\cos\left(4\Phi\right) \qquad (4)$$

For layer 2 it is given by:

$$\begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = \hat{\boldsymbol{\mu}}\begin{pmatrix} h_x \\ h_y \\ h_z \end{pmatrix} = \begin{pmatrix} 1 + k_\alpha^{(2)}\sin^2(\gamma) & -k_\alpha^{(2)}\cos(\gamma)\,s\,in(\gamma) & i\nu\,s\,in(\gamma) \\ -k_\alpha^{(2)}\cos(\gamma)\,s\,in(\gamma) & 1 + k_\alpha^{(2)}\cos^2(\gamma) & -i\nu\cos(\gamma) \\ -i\nu\,s\,in(\gamma) & i\nu\cos(\gamma) & 1 + k_\beta^{(2)} \end{pmatrix}\begin{pmatrix} h_x \\ h_y \\ h_z \end{pmatrix}$$

$$k_\alpha = \frac{\Omega_\alpha}{\Omega_\alpha\Omega_\beta - \Omega^2}, \quad k_\beta = \frac{\Omega_\beta}{\Omega_\alpha\Omega_\beta - \Omega^2}, \quad \nu = \frac{\Omega}{\Omega_\alpha\Omega_\beta - \Omega^2} \qquad (5)$$

$$\Omega = \frac{\omega/\gamma}{4\pi M_s}, \quad \Omega_{\alpha,\beta} = \frac{H_{\alpha,\beta}}{4\pi M_s},$$

where

$$H_\alpha = H + H_A\left[1 - \frac{\sin^2\left(2\Theta\right)}{2}\right]$$
$$H_\beta = H + H_A\cos\left(4\Theta\right). \qquad (6)$$

The fluctuating part of the dipole field **h** and the magnetization **m** must satisfy the magnetostatic form of Maxwell's equations

$$\mathrm{div}\left[\mathbf{h}+4\pi\mathbf{m}\right]=0, \quad \mathrm{rot}\mathbf{h}=0\,. \tag{7}$$

Under the magnetostatic approximation $\mathbf{h}=\mathrm{grad}\left[\psi\exp(\text{-}i\omega t)\right]$, where ψ is a magnetic scalar potential. The problem is now reduced to finding the propagating normal mode solutions for the scalar potential ψ which satisfy the condition (7), that gives simple equation:

$$\mu_{11}^{(i)}\frac{\partial^2\psi}{\partial x^2}+\mu_{22}^{(i)}\frac{\partial^2\psi}{\partial y^2}+\mu_{33}^{(i)}\frac{\partial^2\psi}{\partial z^2}+2\mu_{12}^{(i)}\frac{\partial^2\psi}{\partial x\partial y}=0 \tag{8}$$

where

$$\mu_{11}^{(1)}=1;\mu_{22}^{(1)}=1+k_\alpha^{(1)};\mu_{33}^{(1)}=1+k_\beta^{(1)};\ \mu_{12}^{(1)}=0$$

$$\mu_{11}^{(2)}=1+k_\alpha^{(2)}\sin^2(\gamma);\mu_{22}^{(2)}=1+k_\alpha^{(2)}\cos^2(\gamma);\mu_{33}^{(2)}=1+k_\beta^{(2)};\ \mu_{12}^{(2)}=-k_\alpha^{(2)}\cos(\gamma)\,s\mathit{in}(\gamma);$$

The scalar potential functions $\psi^{(1,2)}$ are taken in the form:

$$\psi^{(1,2)}=\left(a^{(1,2)}\exp\left(k_z^{(1,2)}z\right)+b^{(1,2)}\exp\left(k_z^{(1,2)}z\right)\right)\exp\left(i\kappa_x^{(1,2)}x\right)\exp\left(i\kappa_y^{(1,2)}y\right) \tag{9}$$

$k_z^{(1,2)}$ parameters are related to the propagation wave number $\kappa=\sqrt{\kappa_x^{(1)2}+\kappa_y^{(1)2}}=\sqrt{\kappa_x^{(2)2}+\kappa_y^{(2)2}}$ through Eq.(8):

$$k_z^{(1)}=i\kappa\sqrt{-\left(1+k_\alpha^{(1)}\sin^2(\varphi)\right)\Big/\left(1+k_\beta^{(1)}\right)},\quad k_z^{(2)}=i\kappa\sqrt{-\left(1+k_\alpha^{(2)}\sin^2(\gamma-\varphi)\right)\Big/\left(1+k_\beta^{(2)}\right)} \tag{10}$$

Under the magnetostatic approximation, by imposing the usual electromagnetic boundary conditions, a set of homogeneous equations is generated. The condition for the existence of a nontrivial solution yields the dispersion relation.

$$F_1(\Omega,\kappa d)F_2(\Omega,\kappa d)\text{-}e^{-2kd_p}P_1(\Omega,\kappa d)P_2(\Omega,\kappa d)=0 \tag{11}$$

where

$$F_1(\Omega,\kappa)=\kappa+i\kappa_y\mu_{32}^{(1)}+k_z^{(1)}\mu_{33}^{(1)}\left[(B\exp(2k_z^{(1)}d_1)\text{-}1)\big/(B\exp(2k_z^{(1)}d_1)+1)\right]$$

$$F_2(\Omega,\kappa)=\kappa\text{-}i\kappa_x\mu_{31}^{(2)}\text{-}i\kappa_y\mu_{32}^{(2)}\text{-}k_z^{(2)}\mu_{33}^{(2)}\left[(V\exp(2k_z^{(2)}(d_1+d_p))\text{-}1)\big/(V\exp(2k_z^{(2)}(d_1+d_p))+1)\right]$$

$$P_1(\Omega,\kappa)=\kappa\text{-}i\kappa_y\mu_{32}^{(1)}\text{-}k_z^{(1)}\mu_{33}^{(1)}\left[(B\exp(2k_z^{(1)}d_1)\text{-}1)\big/(B\exp(2k_z^{(1)}d_1)+1)\right]$$

$$P_2(\Omega,\kappa)=\kappa+i\kappa_x\mu_{31}^{(2)}+i\kappa_y\mu_{32}^{(2)}+k_z^{(2)}\mu_{33}^{(2)}\left[(V\exp(2k_z^{(2)}(d_1+d_p))\text{-}1)\big/(V\exp(2k_z^{(2)}(d_1+d_p))+1)\right]$$

$$B=\frac{\kappa\text{-}i\kappa_y\mu_{32}^{(1)}+k_z^{(1)}\mu_{33}^{(1)}}{i\kappa_y\mu_{32}^{(1)}+k_z^{(1)}\mu_{33}^{(1)}\text{-}\kappa},V=\frac{k_z^{(2)}\mu_{33}^{(2)}\text{-}\kappa\text{-}i\kappa_y\mu_{32}^{(2)}\text{-}i\kappa_x\mu_{31}^{(2)}}{k_z^{(2)}\mu_{33}^{(2)}+\kappa+i\kappa_y\mu_{32}^{(2)}+i\kappa_x\mu_{31}^{(2)}}\exp(\text{-}2k_z^{(2)}(2d_1+d_p)),\Omega=\frac{\omega/\gamma}{4\pi M_s}.$$

The dipersion relation includes two parts. One is the product of the individual dispersion of each layer. The other is the coupling term due to the interaction between the two ferromagnetic layers. As the separation between the ferromagnetic layers goes to infinity, than one can obtain the individual dispersion relation for each layer.

NUMERICAL RESULTS

Numerical calculations have been performed to investigate the magnetostatic volume wave properties. The following thicknesses of layers are used: $d_1=1\ \mu m,\ d_2=1\ \mu m,\ d_p=20\ nm$. Specifically, the case of YIG ferrites have been considered ($H=800$ Oe, $H_A^{(1)}=-90$ Oe, $H_A^{(2)}=-86$ Oe, $\Theta=57^o$, $H_U^{(1)}=200$ Oe) [5]. For Fig. 2 and Fig.3, which show the dispersion curves, $M_1=M_2=1750$ G. Fig.4 shows other example of the effects of anisotropy for ferromagnetic layers with different static magnetizations $M_1=1750$ G, $M_2=1256$ G [6].

We can see from Fig. 2-4 the two set of dispersion curves corresponding to layer 1 and layer 2 with different volume mode band limits (Fig. 5). Each set and volume mode band corresponds to the individual magnetic layer. It is important to realize at this point that there is an infinite manifold of volume mod dispersion curves. For the range of kd values, the dispersion curves cover the entire volume mode band for each set. All curves correspond to the roots of transcendental equation (11). In the case of one layer (Fig. 3a), only one set of curves exist.

For YIG materials the volume mode band similar for the band for the isotropic film, except for a surviving band width even at in-plane propogation angle $\varphi=90^o$ (as can be expected, in the limit $\varphi\to90^\circ$ the volume mod band has reduced but has a nonzero width).

As seen from Fig. 2, the propeties of volume magnetostatic modes in that structure are substantially determined by the angle between magnetization vectors in the magnetic layers and the rotation of the direction of propagation in the plane of the film. We can see that splitting between the dispersion curves for layer (1) and layer (2) will rise with a rise in-plane propagation angle φ.

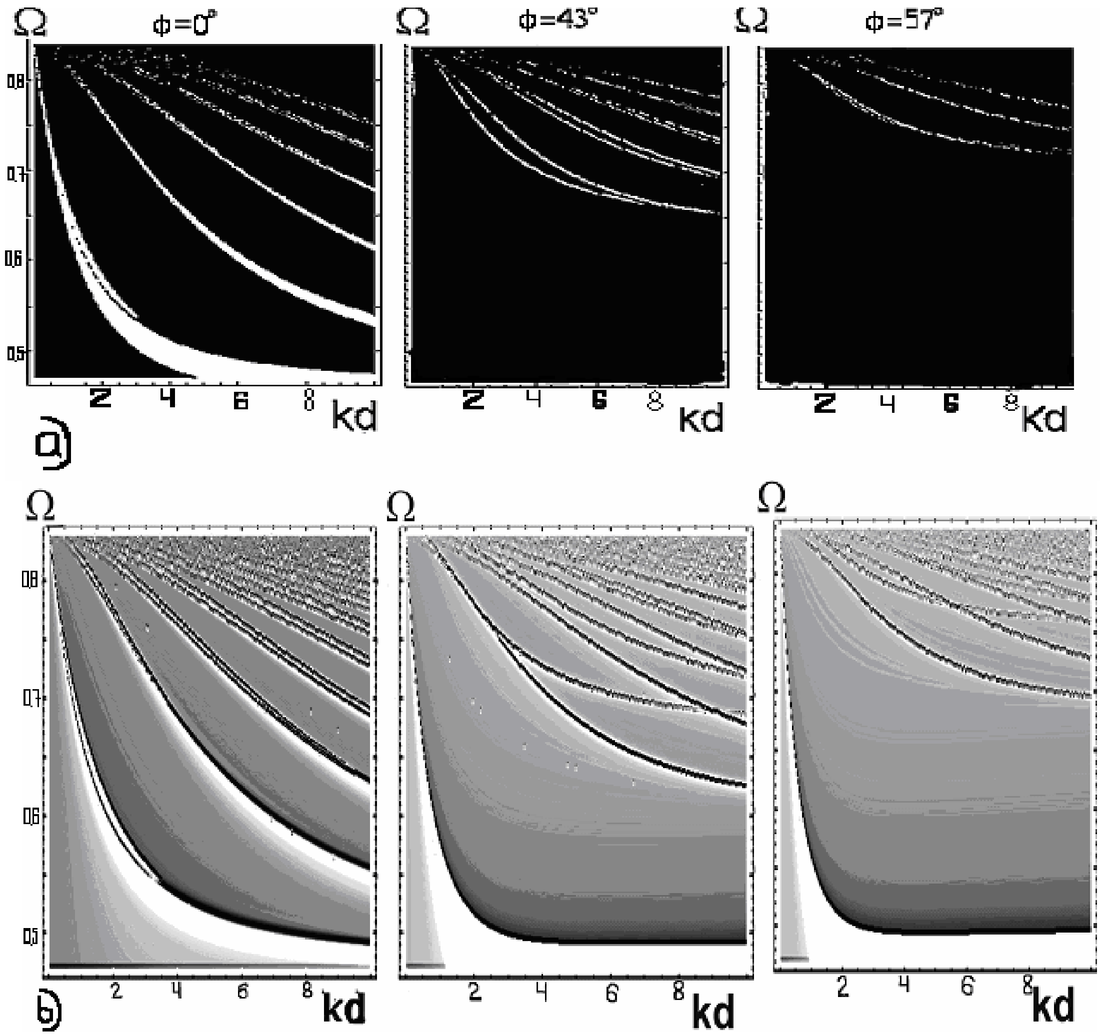


Fig. 2.Dispersion curves of reduced frequency Ω vs. reduced wave number kd for three values of the propagation angle φ.
a)for angle γ=0; b)for angle γ=13^o (γ – angle between magnetization vectors in the magnetic layers)

In Fig. 3(b) (for $M_1 = M_2 = 1750$ G) we can see that the dependence of wave number κ from in-plane propogation angle φ for layer (1) differs from that of layer (2).

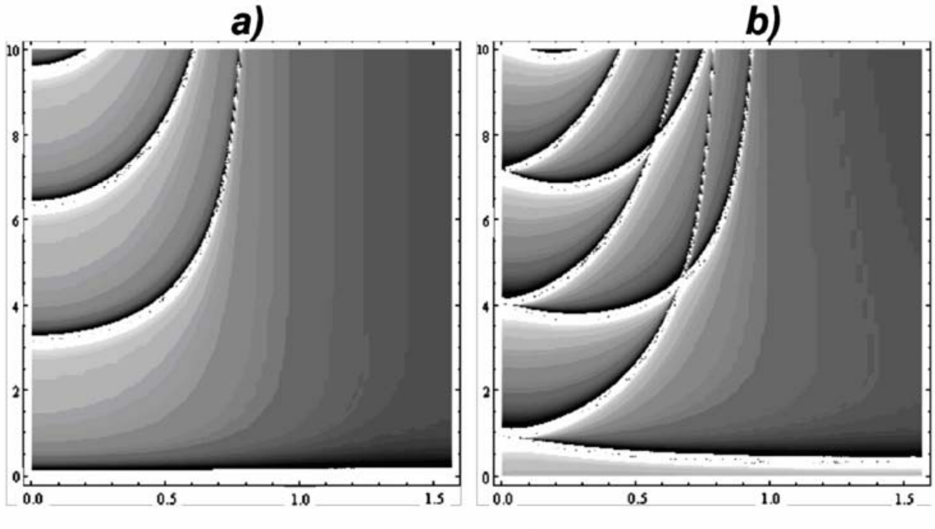


Fig. 3.The reduced wave number kd as a function of in-plane propagation angle φ (reduced frequency Ω=0.8)
a) for one layer, b) for bilayer

Numerical calculations demonstrate that for ferromagnetic layers with different static magnetizations $M_1 = 1750\ G,\ M_2 = 1256\ G$ the dependence of wave number κ from in-plane propogation angle φ can have qualitatively another character than for case ferromagnetic layers with equal static magnetizations.

Similar to Fig. 2, in Fig. 4, for a different propagation direction, the dispersion curves are different.

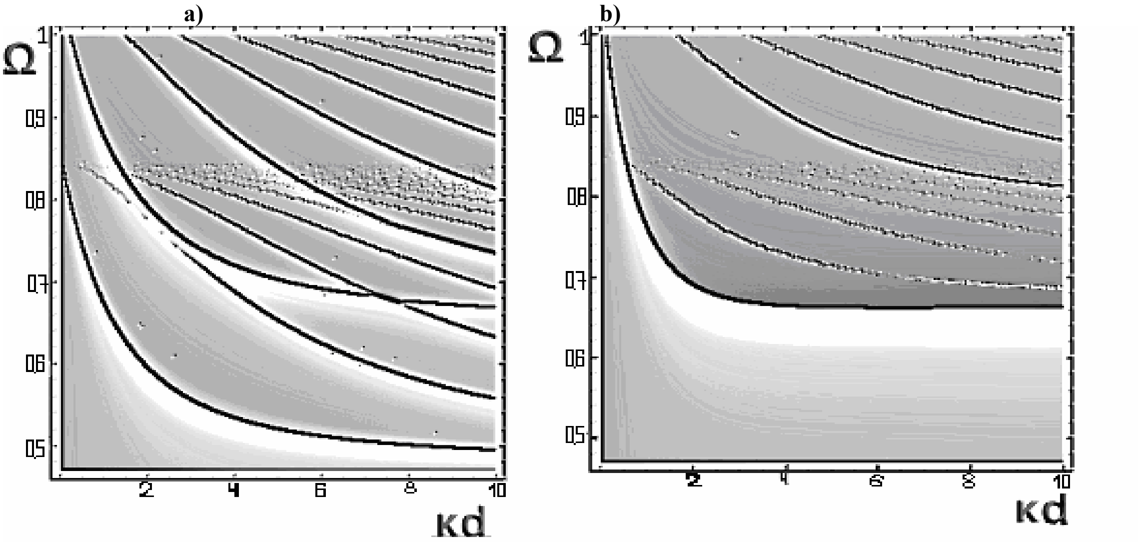
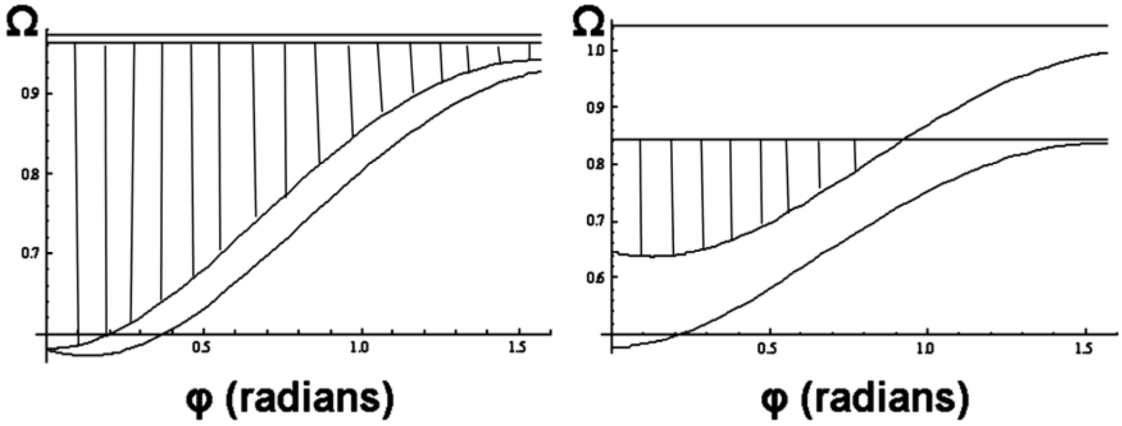


Fig. 4.Dispersion curves of reduced frequency Ω vs. reduced wave number kd .
a) for in-plane propagation angle φ=0; b)for in-plane propagation angle φ=43°

The volume mode bands as a function of in-plane propagation angle φ are shown in Fig.5. It should be pointed out, that contrary article [13], (where the propagation characteristics for backward volume waves were described only for propagation direction parallel to the bias field) in Fig.4 and Fig.5 one can see the overlapping of the volume mode bands for the ferromagnetic layers without any discontinuous. Because of the different static magnetizations in the ferromagnetic layers (Fig.4, Fig.5b), the volume mode band limits for magnetostatic wave excitation for layer (1) strongly differs from that of layer (2).

In the case of the different static magnetizations in the ferromagnetic layers (Fig. 5b), overlapping of the volume mode bands is substantially reduced as compared to Fig. 5a. Also, at that case, as seen from Fig.4 and Fig.5b, the overlapping of the volume mode bands will fall with a rise in-plane propagation angle φ.



a) b)

Fig. 5.The volume mode bands as a function of in-plane propagation angle φ
a) for $M_1 = 1750\ G,\ M_2 = 1750\ G$, b) for $M_1 = 1750\ G,\ M_2 = 1256\ G$

CONCLUSION

This work deals with volume magnetostatic modes of bilayer structure with noncollinear in-plane orientation of magnetization vectors. This is caused by the anisotropy field difference in the layers. The essential dependence of the properties of volume magnetostatic modes is demonstrated on an angle between the magnetization vectors in the layers.

In the case of the different static magnetizations and induced in-plane anisotropy fields in the two different layers the dependence of wave number κ from in-plane propogation angle φ for layer (1) differs from that of layer (2).Also, the difference between static magnetizations reduce overlapping of the magnetostatic waves volume bands.

Since the angle between magnetization vectors in the magnetic layers γ has a strong influence on volume magnetostatic waves propagation the angle between magnetization vectors is a potential control parameter for magnetostatic waves based devices.

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BUKHANKO Artem Fedorovich - Ph.D. in physics and mathematics. Currently working in Donetsk Physicotechnical Institute National Academy of Sciences of Ukraine. His research interests are in the magnetooptics,dynamic properties, solid state physics. He is the author and the co-author 25 scientific publications.