Dispersion of Spin-Electromagnetic Waves in Ferrite-Ferroelectric N-layered Structures

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Abstract

Artificial multiferroics in the form of ferrite-ferroelectric multilayered structures are considered as metamaterials that could be used for increasing functionality of the microwave devices. A theory of quasi-surface spin-electromagnetic waves (SEW) is developed for multilayered ferrite-ferroelectric (FF) structures consisted of several ferrite and ferroelectric layers. Spectra of SEW in the multilayered structures are numerically simulated. An influence of the different FF structure parameters on the dispersion of SEW is analyzed.

1. Introduction

One of the simplest ways to create artificial metamaterial is to use multiferroics that combine both ferroelectric and ferromagnetic properties. One of the advantages of such structures is possibility to dual tuning by changing external electric and magnetic fields. There are two main research directions of the multiferroics. The first of them is investigation of the single-phase natural multiferroic materials that have ferroelectric and ferromagnetic properties simultaneously. The second direction is investigation of layered heterostructures (ferromagnetic and ferroelectric phases are in a different layers) [1, 2]. It was shown that spin waves may interact with electromagnetic waves in the ferrite-ferroelectric structures. This interaction was called hybridization. Value of the electric tuning in this case bigger than in the case of natural multiferroics. Consequently spin-electromagnetic waves propagating in the FF structures may find a wide variety of applications. In particular, the structures can be used for development of the dual-tunable microwave devices [3-4]. Spectra of SEW in multilayered FF structures consisted of *one ferrite* layer and several ferroelectric layers was investigated [5]. At the same time, spectra of the SEW in the case of complex multilayered structures composed of *several ferrite* layers and several ferroelectric layers was not studied yet. Purposes of the present work are to develop theory of a spectrum of spin-electromagnetic waves in multilayered ferrite-ferroelectric structures consisted of several ferrite and ferroelectric layers.

2. Theoretical model

A ferrite-dielectric multilayer consists of one dielectric layer with thickness a on the "ideal" metal and interchange of ferrite and dielectric layers with thicknesses a_{2i} and a_{2i+1} correspondingly, where i is a layer number. Arbitrary one or several dielectric layers could be ferroelectrics by means of high dielectric permittivity. Investigated structure is infinite in xz plane and magnetized to the saturation along x axis. Electromagnetic waves propagates along z axis. In order to find SEW spectrum, it is necessary to solve Maxwell`s equation containing tensor of permeability obtained from equation of mo-

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tion [6]. The SEW theory is developed for exchangeless quasi-surface spin-electromagnetic waves in single mode regime and in lossless approximation. Absence of bounds in the *x* direction gives possibility to divide electromagnetic waves in this structures into TE and TM modes. It was shown that TE modes of electromagnetic waves has the field distributions similar to the surface SW [5]. It leads to relatively strong interaction between them. Therefore, we will consider only TE modes of spectrum of electromagnetic waves. On the next step Helmholtz equations are founded from Maxwell equations for every layer. Unknown coefficients in the solutions of these equations are connected with each other by electrodynamic boundary conditions. Such connections between coefficients gives possibility to find them through transfer matrixes $\mathbf{M}_i$ and $\mathbf{N}_i$. Therefore, continuity of all tangential components of the fields gives possibility to express coefficient in the first layer through coefficient in the free space (with number *n*)

$$[A, A] = \mathbf{M}[A_n, A_n], \qquad (1)$$

where $\mathbf{M} = \left((\mathbf{M}_0)^{-1}\cdot\mathbf{N}_0\right)\left((\mathbf{M}_1)^{-1}\cdot\mathbf{N}_1\right)\ldots\left((\mathbf{M}_{2i-1})^{-1}\cdot\mathbf{N}_{2i-1}\right)\left((\mathbf{M}_{2i})^{-1}\cdot\mathbf{N}_{2i}\right)\ldots\left((\mathbf{M}_{n-1})^{-1}\cdot\mathbf{N}_{n-1}\right)$. Dispersion equation in this case is:

$$f(\omega, k) = -\mathrm{M}_{21} - \mathrm{M}_{22} + \mathrm{M}_{12} + \mathrm{M}_{11}. \qquad (2)$$

Thereby transfer matrixes $\mathbf{M}_{2i-1}$, $\mathbf{N}_{2i-1}$ and $\mathbf{M}_{2i}$, $\mathbf{N}_{2i}$ gives possibility to obtain dispersion equation of SEW in the FF structure that consist of *several* ferrites layers interchanging with dielectric or/and ferroelectric layers.

3. Numerical modeling

To verify theoretical model we calculate a SEW spectrum for the case of one ferrite layer in FF structure. All simulation results are in a good agreement with the previously reported data [4, 6]. On the next step we simulate SEW spectra for more complicated structures that consist of more than one ferrite layers (fig. 1.*a*). The structure consists of two separate ferrite layers (it could be yttrium iron garnet films on gadolinium gallium garnet substrates) and one ferroelectric layer between them (for example barium strontium titanate ceramics). In the simulation we use typical parameters for such materials. Figs. 1.*b* and 1.*c* gives possibility to explain formation and features of SEW spectra in the FF heterostructures that are shown in the Fig. 1.a.

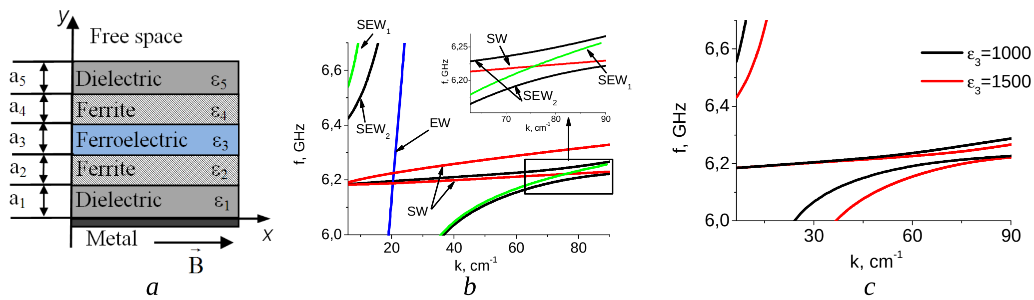
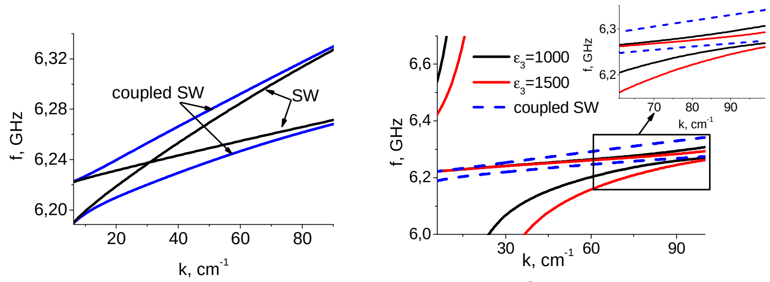


Fig. 1.*a*: FF multilayered structure consisted of two ferrite layers separated by ferroelectric layer; *b*: Spectra of the waves in the multilayered FF structures (H=1500Oe, a_2=20 μm, a_4=6 μm, M_2=M_4=1750 G); *c*: Electric tunability of dispersion characteristic of SEW in the FF multilayered structure (parameters are the same)

At first we analyse structures in the case of different thicknesses of the ferrite layers (a_2=20 μm and a_4=6 μm) but equal saturation magnetizations (M_2=M_4=1750 G). Thickness of the ferroelectric layer was a_3=200 μm. Fig. 1.*b* shows: SW (red lines) in the structure consisted of two ferrite layers separated by 200 μm of free space (ε_3=1); EW (blue line) in the structure (Fig.1.*a*) which are placed outside of magnetic field and ε_3=1500; SEW_1 in the structure included only one ferrite layer (M_2= 1750

G, M_4=0 G). There are two hybridization zones (Fig. 1.*b*). The first zone (20 cm^{-1}) is due to hybridization between SW in the thick (20μm) ferrite layer and EW. The second zone (80cm^{-1}) is due to hybridization between SW in the thin ferrite layer (6 μm) and SEW_1 in the FF based on the one ferrite layer. As a result, spectrum of the SEW_2 in the structure that is shown in the Fig. 1.*a* consists of three dispersion branches (Fig. 1.*b*). An influence of the ferroelectric layer permittivity on dispersion characteristics is shown in the Fig. 1.*c*. Change in the ferroelectric layer permittivity gives possibility to realize electric tuning of the SEW spectra. Tuning of wave numbers increases close to SW frequencies. Consider now a structure having a different thicknesses and saturation magnetizations of the ferrite layers. The most interesting situation takes place if saturation magnetization in the thin layer is slightly bigger than in the thick layer. In this case dispersion characteristics of SW in such layers have the point of quasi-intersection (black lines in the Fig. 2.*a*). If we start to decrease distance between ferrite layers, the waves become coupled. Dispersion of the coupled spin waves for the case of free space between ferrite layers is shown in the Fig. 2.*a*. (blue lines). For calculation the distance between the layers was chosen to be a_3=200 μm. Spectra of the SEW in the FF structure containing a ferroelectric layer between the ferrite layers is shown in Fig.2. Here the situation is similar to Fig. 1.*b*. Namely, the first hybridization occurs between EW and upper branch of coupled SW and second hybridization occurs between SEW and lower branch of SW.



a *b*

Fig. 2.a: Spectra of the SW of in the separate ferrite layers (black lines) and spectrum of the coupled SW (blue lines). H=1500Oe a_2=20 μm, a_4=6 μm, a_3=200 μm, M_2=1750 G, M_4=1790 G, ε_3=1; b: Electric tunability of dispersion characteristic of SEW in the FF multilayered structure (parameters is the same)

4. Conclusion

Developed theoretical model gives possibility to investigate wide range of problems connected with hybrid SEW in the ferrite-ferroelectric multilayered structures. Dispersion equation of SEW in these structures was found. Spectra of SEW in FF structures consisted of two ferrite layers separated by ferroelectric layer was investigated. Electric field tuning of SEW spectra was demonstrated. An increasing in a number of ferrite layers makes SEW spectra more complicated that provide flexibility for MW device design.

References

[1] C. Nan, M. I. Bichurin, S. Dong, D. Viehland, G. Srinivasan, *Multiferroic magnetoelectric composites: Historical perspective, status, and future directions*, J. Appl. Phys., vol. 103, pp 031101-35, 2008.

[2] U. Ozgur, Ya. Alivov, H. Morkoc, *Microwave ferrites, part 2: passive components and electrical tuning*, J. Mater Sci: Mater Electron, vol. 20, pp. 911–952, 2009.

[3] V. E. Demidov, P. Edenhofer, B. A. Kalinikos, *Electrically tunable microwave phase shifter based on layered ferrite-ferroelectric structure*, Electronics Letters, vol. 37, Is. 19, pp. 1154-1156, 2001.

[4] A.B. Ustinov, V.S. Tiberkevich, G. Srinivasan et. al., *Electric field tunable ferrite-ferroelectric hybrid wave microwave resonators: Experiment and theory*, J. Appl. Phys., vol. 100, pp. 093905-7, 2006.

[5] V. E. Demidov, B. A. Kalinikos, P. Edenhofer, *Dipole-exchange theory of hybrid electromagnetic-spin waves in layered film structures*, J. Appl. Phys, vol. 91, pp. 10007-10, 2002.

[6] D.D. Stancil, A. Prabhakar, *Spin Waves: Theory and Applications*, Springer, 2009.

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