Electrodynamical properties and modes of finite-width planar ferrite waveguide

A.V. Sadovnikov¹, K.V. Bublikov¹
¹Saratov State University, Saratov, 83 Astrakhanskaya str., 410012, Russia

E-mail: SadovnikovAV@gmail.com

Abstract. The present work focuses on the detailed study of the processes of electromagnetic wave propagation in finite-width planar ferrite film. The method of computation of electrodynamical characteristics of finite-width ferrite waveguide is proposed. The efficiency of method is estimated. Different boundary conditions are used and compared.

1. Introduction
Planar ferrite waveguide structures fabricated from thin film of yttrium iron garnet (YIG) can be used as basic elements of various functional devices. In spintronics and magnetoelectronics this structures applied for waveguides, couplers, delay lines and filters [1]. The electrodynamical characteristics of YIG-based devices can be changed in a wide range due to the possibility of operation frequency tuning of these devices by an external magnetic field, the existence of variety of the dispersion types of propagating waves (surface and volume, forward and backward). Considering the wave propagation process in the finite-width ferrite thin film waveguides one has to determine the spectrum and the dispersion characteristics of the waveguide modes, group delay, attenuation coefficients and excitation conditions. The excitation spectrum of magnetostatic surface spin waves (MSSW) in regular finite-width ferrite waveguide was widely investigated [2], but the multimode MSSW propagation in planar ferrite waveguides requires more detailed consideration.

2. Numerical modulation of ferrite-based waveguide.
Many theoretical and numerical methods of studying of wave propagation process in thin ferrite waveguide have been developed, including micromagnetic simulations and the plane wave method. In the present work finite element method (FEM) was used to simulate wave equation, obtained directly from Maxwell equations [3,4].

Geometries of computational cell are depicted in figure 1, a, c. The Damon-Eshbach (DE) spin waves geometry was considered in numerical simulation, the external field is oriented along the x-axis. The details of numerical method is presented in work [4]. Perfect electric conductor (PEC) or perfect magnetic conductor (PMC) [3] was placed on the left and right borders of computational cell and PEC was placed on the bottom and top borders. Two main configuration of computational domain was considered: right and left boundaries of YIG film.
Figure 1. Geometry of computational cell (the waveguide xy-section) for different methods of numerical simulation: (a) – (c) and the corresponding meshes for FEM solver (b,d).

The schematic pictures of considered structures are shown in Figure 1 a, c. The ferrite film bounded on the left and right side with PMC or PEC (figure 1, a). The YIG film which is not bounded by the PMC or PEC is shown in figure 1, c. This structure will be referred to as open YIG wave guide because the magnetic and electric fields mainly concentrated in the area of ferrite film. The corresponding meshes used in FEM simulation are shown in figure 1, b, c. The width of the computational cell is $L$, the width of the open waveguiding YIG structure is $l$. The parameters $L$ and $l$ were varied in the numerical modeling. The upper and lower boundaries of the computational areas were chosen to be a PEC.

The value of the external bias magnetic field was $H_0=300$ Oe, saturation magnetization of YIG film was $4\pi M_0=1750$ G. The results of dispersion computation of structure depicted in figure 1, a with PMC at the left and right borders of computational area (coincided with left and right borders of YIG film) are presented in figure 2.

Figure 2. The results of FEM simulation (dispersion of the waveguide from figure 1, a) with PMC. D.E. means the Damon-Eshbach magnetostatic wave.

Figure 3. Distribution of the electrical and magnetic fields of the waveguide from figure 1, a with PMC as a boundary condition on the left and right sides of the structure.
Figure 4. Dispersion of the YIG-waveguide from figure 1 a with PEC boundary conditions.

Figure 5. The electrical and magnetic fields distribution in the computation cell with YIG-waveguide from figure 1 a with PEC as a boundary condition on the left and right sides of the structure.

Figure 6. The results of modulation waveguide from figure 1 c with magnetic walls. Continuous line is analytical results from [5].

Figure 7. The electrical and magnetic fields distribution along x-axis of YIG-waveguide from figure 1 c. Vertical lines shows edges of YIG film.
Two different values of the width of structure was considered ($L=60 \, \mu m$ and $L=1000 \, \mu m$). The multimode nature of distribution of magnetic and electric fields and a good correspondence between the computed dispersion for the structures with $L=1000 \, \mu m$ and the Damon-Eshbah [3] magnetostatic wave (which described the unbounded YIG film in $x$-direction). The considerable transformation of dispersion with a decrease of $L$ are observed in FEM simulation.

The results of numerical simulation of the same structure (figure 1 a) with PEC in the left and right borders of computation cell is depicted in figure 4. In this configuration of computation cell the zero mode of the metallic rectangular waveguide can be obtained in FEM simulation. It has been shown that the dispersion of this mode doesn’t change with the changing the width of waveguide and computation cell $L$ therefore.

The distributions of $|E|$ and $|H|$ field in cross-section of YIG-waveguide both for the case of metallic and magnetic walls in the left and right borders of computation cell were shown in figure 3 and figure 5. We can see influence of boundary conditions on distribution of fields. The uniform distribution of of $|E|$ and $|H|$ fields along $x$-axis for zero mode is shown in figure 5 for wavenumber $k=700 \, cm^{-1}$.

The results of numerical simulation of an open waveguide (figure 1 c) are presented in figure 6 and figure 7. The rapid decrease of the $|E|$ and $|H|$ components near the borders (see figure 6) demonstrates the possibility to consider this structure to be a similar to ferrite film without metallic or magnetic walls on the boundaries. The estimation of difference between analytical results (from work [2]) and FEM simulation of structure in figure 1 a (with PEC) and figure 1 c (with PMC) is depicted in figure 8. For this purpose we will enter variable $\delta$, which is defined as:

$$\delta(f) = \left| \frac{k_{FEM} - k_{OK}}{k_{FEM}} \right| \cdot 100\%,$$

where $k_{FEM}$ is the FEM simulation result and $k_{OK}$ is analytical calculation of finite-width dispersion in magnetostatic approximation [2]. The difference for structure, depicted in figure 1 a, is less than 5%, and for structure, depicted in figure 1 c, is less than 1%. In both cases the maximum differences is observed in the region of small wavenumbers. It can be explained with influence of borders on the localized fields at this wavenumbers. This effect is impossible be considered in magnetostatic approach.

3. Summary

The detailed study of the processes of electromagnetic wave propagation in finite-width planar ferrite film was performed with FEM computation. The efficiency of method of electrodynamical characteristics computation was estimated. Different boundary conditions were used and compared in the FEM simulation of Maxwell’s system of equations. The surface magnetostatic waves were considered. Decrease the width of a YIG-film leads to the increase of the wavenumber of surface wave at fixed frequency. Electric and magnetic field distribution at different boundary conditions can explain the differences with magnetostatic approach, which are clearly seen at the small wavenumber region ($k \sim 100 \, cm^{-1}$).
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**References**

[1] Lenk B, Ulrichs H, Garbs F and Münzenberg M 2011 Physics Reports 507 107
[2] O’Keffe T W and Patterson R W 1973 J. Appl. Phys. 49 4886
[3] Silvester P P and Ferrari R L 1996 Finite Elements for Electrical Engineers (3rd edition). Cambridge University Press
[4] Sadovnikov A V and Rozhnev A G 2012 Appl. Nonlinear Dyn. 20 143
[4]. Damon R W, Eshbach 1961 J R J. Phys. Chem. Solids. 19 308
[5] Camley R E 1987 Surface Science Reports. 7 103.