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MAGNETISM

Ferromagnetic Resonance in Interacting Magnetic Microstrips

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Abstract—The results of the micromagnetic simulation of forced oscillations of the magnetization in a system of two interacting microstrips located at an angle to each other have been presented. The ferromagnetic resonance spectra and the mode composition of resonant oscillations of the system have been investigated under the conditions of magnetostatic and exchange interactions between the microstrips. It has been shown that the magnetostatic interaction leads to the possibility of the excitation of in-phase and out-of-phase coupled oscillations of the magnetization of the microstrips. In the systems of exchange-coupled microstrips, there are intense resonances due to oscillations of the domain walls. The transformation of the ferromagnetic resonance spectrum and the change in the mode composition of resonant oscillations in different equilibrium configurations of the magnetization of the system have been discussed, as well as the conditions for the excitation of oscillations of different types depending on the direction of the microwave magnetic field.

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1. INTRODUCTION

Ferromagnetic nanostructures have traditionally attracted the attention of many research groups due to the prospects of their application in information storage devices and microwave nanoelectronics [1–3]. In recent years, the development of modern nanolithography methods has opened up possibilities for the creation of ultradense planar structures with characteristic dimensions of the elements of the order of 100 nm and a distance between the elements of up to 10 nm [4–6]. These systems exhibit significant effects of magnetostatic and exchange interactions. In particular, a large number of works have been devoted to the study of the influence of size effects on the microwave properties of ferromagnetic nanosystems [7–17].

One of the main methods of theoretical investigation of microwave properties exhibited by ferromagnetic nanostructures is the simulation based on the numerical solution of the Landau–Lifshitz equation. In the majority of the studies in this field, the ferromagnetic resonance spectrum is calculated using the Fourier analysis of relaxation oscillations excited by a pulsed magnetic field [14, 15]. This method makes it possible to quickly calculate the eigenfrequencies of the system under investigation. However, it cannot provide information about the efficiency of the excitation of one or another oscillation mode by an external alternating magnetic field. In this work, we have investigated the effect of the exchange and magnetostatic interactions on the microwave properties of systems with a noncollinear equilibrium distribution of the magnetic moment. Moreover, we have analyzed the influence of an equilibrium configuration of the magnetization and the direction of a microwave magnetic field on the mode composition of the ferromagnetic resonance spectrum. From the practical point of view, the interest in this area of research is associated with the prospects for use of magnetic nanostructures in the development of tunable resonators and passive filters operating in the gigahertz frequency range [18, 19].

2. COMPUTATIONAL TECHNIQUE

The ferromagnetic resonance spectra and the mode composition of the magnetization oscillations in systems composed of two interacting microstrips made of permalloy $Ni_{80}Fe_{20}$ were investigated using the numerical simulation. The simulation was performed based on the numerical solution of the Landau–Lifshitz–Gilbert equation for the magnetization of the sample with the standard object oriented micromagnetic framework (OOMMF) code [20]. The calculations were carried out using the following parameters of $Ni_{80}Fe_{20}$: the saturation magnetization was 8×10^5 A/m, the exchange constant was 8.4×10^{-12} J/m, the dissipation constant was 0.01, and the crystallographic anisotropy was ignored. The computational cell had the size of $10 \times 10 \times 30$ nm, which is sufficient for the description of inhomogeneous oscillations of the magnetization in the experimentally attainable frequency range (1–20 GHz). The microstrips had a

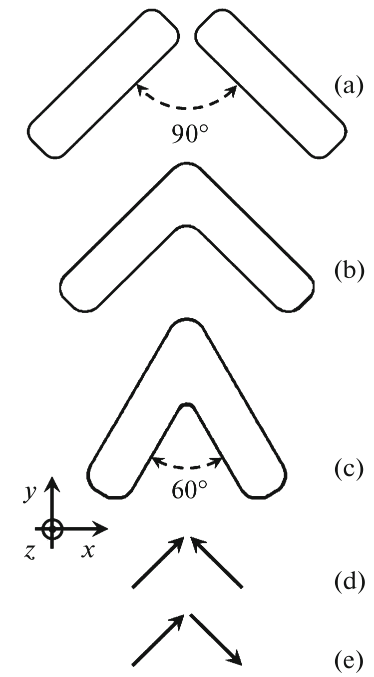

Fig. 1. Systems of interacting microstrip: (a) the system of individual microstrips tilted with respect to each other at an angle of 90° (system I), (b) the coupled microstrips tilted with respect to each other at an angle of 90° (system II), (c) the coupled microstrips tilted with respect to each other at an angle of 60° (system III), (d) the state of the magnetic moments of the microstrips H–H, and (e) the state of the magnetic moments of the microstrips H–T.

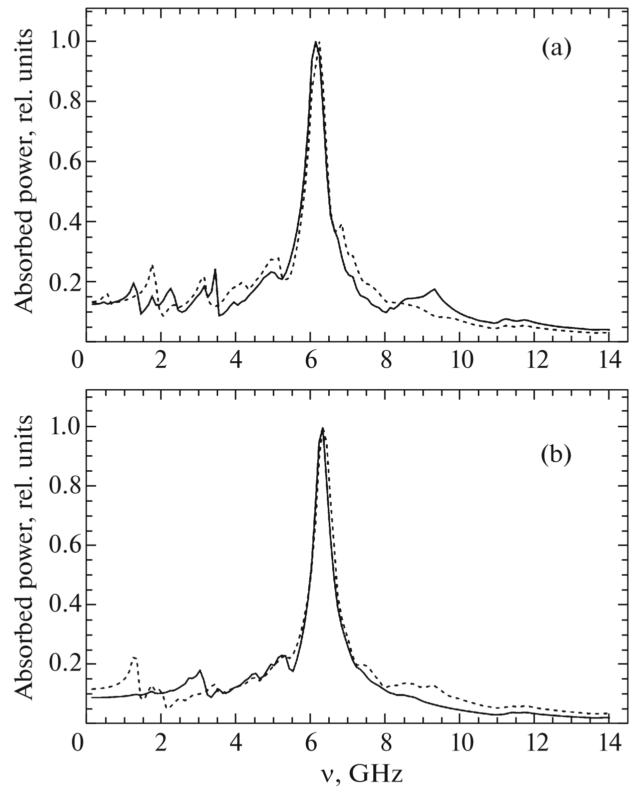

Fig. 2. Model spectra of system I for the configurations (a) H–H and (b) H–T. The solid and dashed lines represent the spectra obtained for alternating magnetic fields applied along the *x* and *y* axes, respectively.

characteristic size of 2000 × 500 × 30 nm. In the simulation of the magnetization oscillations, initially, the system was brought to equilibrium. Then, an alternating magnetic field was applied to the equilibrium system, and the steady-state oscillation amplitude proportional to the absorbed microwave power was measured. The frequency of the excitation microwave field was varied in the range from 0 to 14 GHz with a step of 0.1 GHz. No constant external magnetic field was applied. For the analysis of the mode composition of the resonances, we calculated the time dependences of the spatial distributions of magnetization oscillations (amplitudes of the z-component).

3. RESULTS AND DISCUSSION

We investigated three systems. The first system (system I, Fig. 1a) is formed by two particles so that the angle between their long axes is equal to 90° and the gap between their edges is 100 nm. In the second system (system II, Fig. 1b), the angle between the axes of the particles is also equal to 90°, but the particles are bound to each other; i.e., they are exchange-coupled. In the third system (system III, Fig. 1c) the angle between the axes of the particles is equal to 60°, and the particles are also bound to each other. Each of these systems can be in two stable states, which correspond to the configuration "head-to-head" (H–H) (Fig. 1d) or the configuration "head-to-tail" (H–T) (Fig. 1e). The transitions of the system from one state to another occur under the action of an external magnetic field pulse (the characteristic magnetization reversing field is ~200 Oe).

The interaction occurring in the systems under investigation gives rise to collective oscillations. In this case, by changing the method for the excitation of oscillations (the direction of an alternating microwave magnetic field), it is possible to control the microwave absorption spectrum, because the intensity of different modes depends on the excitation conditions. In particular, in these systems, there are quasi-homogeneous oscillation modes, namely, quasi-optical (out-of-phase coupled oscillations) and quasi-acoustic (in-phase coupled oscillations). Each of these modes can be excited separately by applying an alternating magnetic field along the x or y axis (the directions of the axes are shown in Fig. 1).

The model spectra of system I are shown in Fig. 2. The intense peaks in these spectra correspond to the excitation of the quasi-optical and quasi-acoustic modes. For the H–H configuration, the quasi-acoustic mode is excited when the alternating magnetic field is applied along the x axis (the spectrum is shown by

Fig. 3. Spatial distributions of the magnetization oscillations (amplitudes of the z-component) in system I for the H–H configuration: (a) quasi-optical mode and (b) quasi-acoustic mode.

the solid line in Fig. 2a), whereas the quasi-optical mode is excited by an alternating magnetic field applied along the y axis (the spectrum is shown by the dashed line in Fig. 2a). For the H–H configuration, the quasi-acoustic mode is excited upon application of the alternating magnetic field along the y axis (the spectrum is shown by the dashed line in Fig. 2b), while the quasi-optical mode is excited by applying the alternating magnetic field along the x axis (the spectrum is shown by the solid line in Fig. 2b).

As an example, Fig. 3 shows the spatial distributions of the amplitudes of magnetization oscillations in the quasi-optical and quasi-acoustic modes for the H–H configuration of system I. It can be seen from Fig. 3 that the resonant oscillations represent a superposition of the quasi-homogeneous mode and different modes of longitudinal spin-wave resonance. This is associated with the nonmonotonicity of the dispersion characteristic of spin waves propagating along the long axis of the microstrip, which leads to the degeneration of the frequency; i.e., for one value of the frequency, there are two spin-wave modes [14]. However, the spin-wave modes with a high spatial frequency make a weak contribution to the intensity of the resonance peaks due to the smallness of the overlap integral in the expression for the mode excitation coefficients [21]. The other low-intensity peaks are attributed to resonant oscillations of small inhomogeneous regions in the magnetization distribution of the microstrips. The tuning of the frequency of the main resonance in system I with a change in the magnetization configuration does not exceed 0.2 GHz.

The model spectra of system II are shown in Fig. 4. The resonant oscillations of system II, which correspond to the main peak, are similar to the quasi-homogeneous modes of system I. The tuning of the frequency of the main peak with a change in the magnetization configuration for system II reaches 0.8 GHz. However, the combination of two particles in one "corner" leads to the fact that, in this system, there arise two domain walls in the magnetization distribution, which corresponds to the H–H state, and one domain wall in the H–T state (Fig. 5). The regions of domain walls are additional oscillators interacting with other parts of the system. Consequently, the spectra exhibit the corresponding additional resonance peaks.

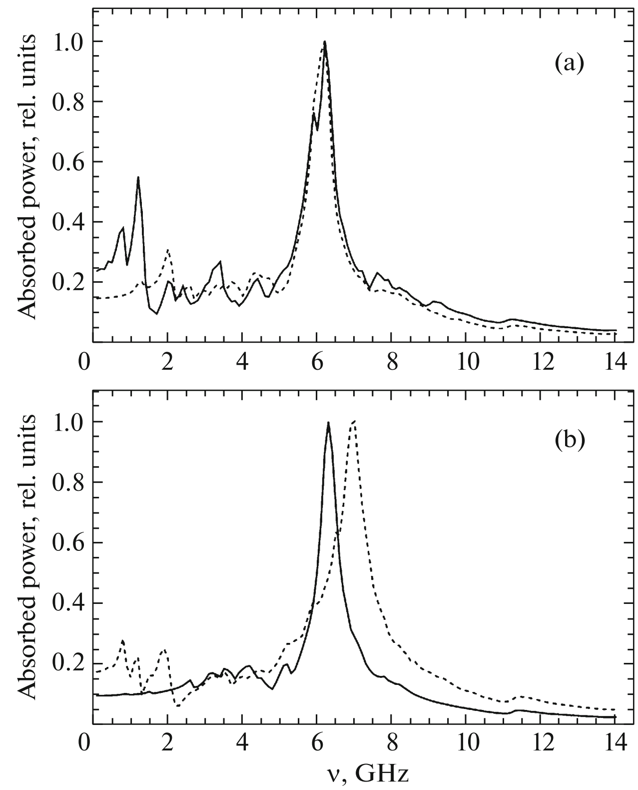

Fig. 4. Model spectra of system II for the configurations (a) H–H and (b) H–T. The solid and dashed lines represent the spectra obtained for alternating magnetic fields applied along the x and y axes, respectively.

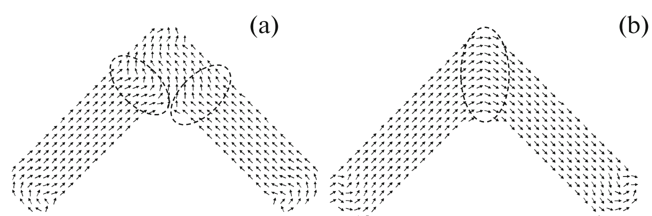

Fig. 5. Equilibrium magnetization distributions in system II for the configurations (a) H–H and (b) H–T. Ovals indicate regions of domain walls.

In system II, the presence of domain walls in the H–H configuration (Fig. 5a) leads to the appearance of a rather intense peak at the frequency $\nu = 1.2$ GHz in the spectrum upon application of the magnetic field along the x axis. The distribution of the amplitudes of the magnetization oscillations corresponding to this resonance is shown in Fig. 6. It can also be seen from Fig. 6 that there is a resonance near the edge of the microstrip due to the inhomogeneity of the magnetization in this region. It should be noted that, upon

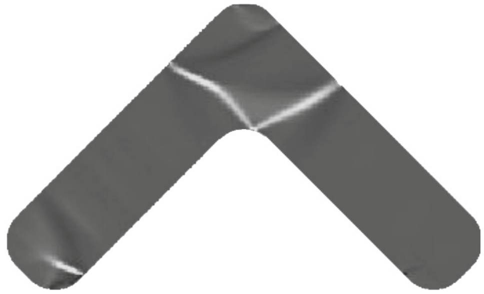

Fig. 6. Spatial distribution of the resonant magnetization oscillations (amplitudes of the *z*-component) in system II for the H–H configuration at the frequency ν = 1.2 GHz. The alternating magnetic field is applied along the *x* axis.

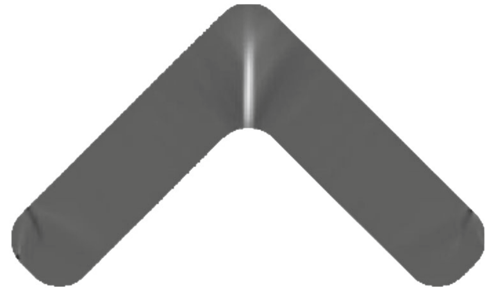

Fig. 7. Spatial distribution of the magnetization oscillations (amplitudes of the *z*-component) in system II for the H–T configuration at the frequency ν = 1.9 GHz. The alternating magnetic field was applied along the *y* axis.

application of an alternating magnetic field along the *y* axis, this resonance is less efficiently excited (see the spectrum in Fig. 4a). This is associated with the fact that the magnetization distribution in the domain walls for this configuration has a preferred direction along the *y* axis. Therefore, the application of the microwave magnetic field along the *x* axis leads to a more efficient excitation of the resonance.

For the H–T configuration and the direction of the alternating magnetic field along the *y* axis, there is also a significant resonance corresponding to the fundamental oscillation of the domain wall (Fig. 7). Moreover, the alternating magnetic field directed along the *x* axis hardly excites oscillations of the domain walls, which, as in the previous case, is associated with the specific features in the magnetization distribution (the magnetization is directed predominantly along the *x* axis (Fig. 5b)).

The model spectra of system III are shown in Fig. 8. As in the case of system II, the spectra of system III exhibit quasi-homogeneous modes and modes of oscillations of the domain walls. The magnetization distributions for the configurations H–H and H–T are shown in Fig. 9.

For the H–H configuration, as well as for system II, the spectra of system III contain a rather intense peak at the frequency ν = 1.2 GHz (Fig. 10a), which corresponds to the resonance attributed to the domain wall. This resonance is well excited by the alternating magnetic field directed both along the *x* axis and along the *y* axis. This is associated with the fact that the equilibrium configuration of the magnetization in domain walls for system III has no preferred direction along any of the axes. The other peaks shown in Fig. 8a are consistent with the spin-wave resonances. Figure 10b shows the spatial distribution of the magnetization oscillations of one of the modes corresponding to the spin-wave resonance at the frequency ν = 4.4 GHz.

For the H–T configuration and the direction of the alternating magnetic field along the *x* axis, the spectrum contains several intense resonance peaks (Fig. 8b). In addition to the quasi-homogeneous mode with a frequency ν = 6.1 GHz, there are peaks attributed to oscillations of the domain wall at frequencies ν = 1.3 and 8.4 GHz. The corresponding distributions of the magnetization oscillations are shown in Fig. 11. The resonance at the frequency ν = 1.3 GHz is similar to the resonance of system II at the frequency ν = 1.9 GHz. As in system II, this resonance is excited by an alternating magnetic field directed along the *y* axis. The resonant oscillations of the magnetization inside the domain walls can be described by the num-

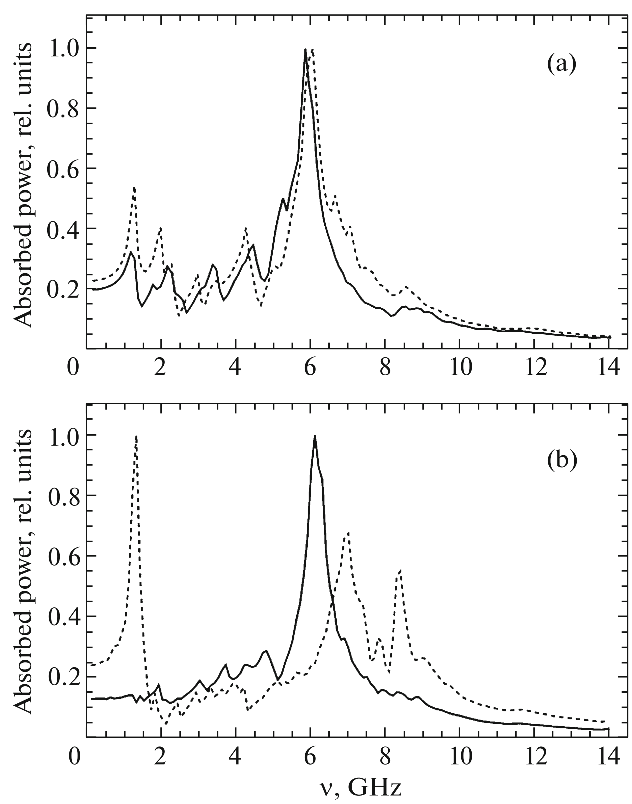

Fig. 8. Model spectra of system III for the configurations (a) H–H and (b) H–T. The solid and dashed lines represent the spectra obtained for alternating magnetic fields applied along the *x* and *y* axes, respectively.

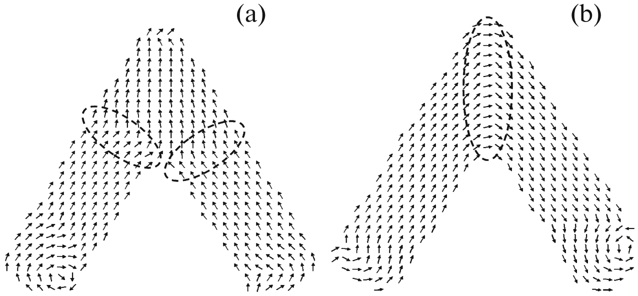

Fig. 9. Equilibrium magnetization distributions in system III for the configurations (a) H–H and (b) H–T.

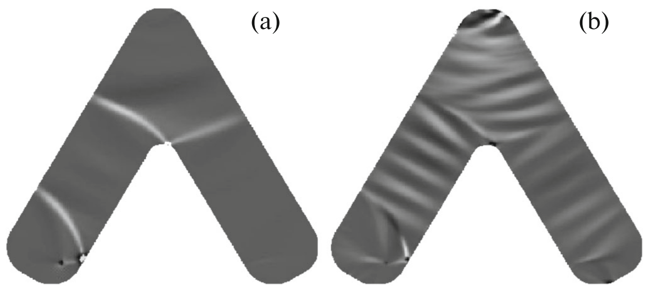

Fig. 10. Spatial distributions of the magnetization oscillations (amplitudes of the *z*-component) in system III for the H–H configuration at frequencies ν = (a) 1.2 and (b) 4.4 GHz. The alternating magnetic field is applied along the *x* axis.

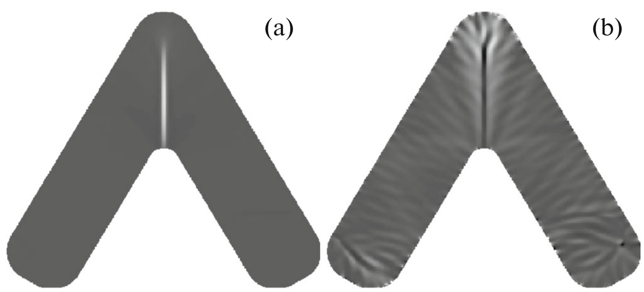

Fig. 11. Spatial distributions of the magnetization oscillations (amplitudes of the *z*-component) in system III for the H–T configuration at frequencies ν = (a) 1.3 and (b) 8.4 GHz.

ber of half-wavelengths fit into it in the same way as it is done for uniformly magnetized microstrips [14]. The peak located at the frequency ν = 8.4 GHz is attributed to the oscillation of the domain wall with a number of half-waves equal to three (Fig. 11b).

Resonance frequency (in GHz) of the quasi-homogeneous mode for different systems of interacting magnetic microstrips

Configuration	I	II	III
H–H, the field along the *x* axis	6.1	6.2	5.8
H–H, the field along the *y* axis	6.2	6.2	6.0
H–T, the field along the *x* axis	6.3	6.3	6.1
H–T, the field along the *y* axis	6.3	7.0	7.0

For comparison, the table presents the frequencies of quasi-homogeneous modes for all the magnetization configurations under investigation. It can be seen that the maximum changes in the positions of the resonance peaks are observed for systems II and III due to a stronger magnetostatic interaction between the microstrips.

The analysis of the results obtained demonstrates that the maximum change in the frequency of the resonance, which corresponds to the quasi-homogeneous modes, with the change in the magnetization configuration is observed in system III and amounts to 1 GHz. On the other hand, the positions of the resonance peaks corresponding to oscillations of the domain wall are sensitive to the magnetization configuration and the orientation of the system with respect to the alternating magnetic field. In particular, for system III in the H–T configuration, when the microwave field is directed along the *y* axis, the spectrum contains the resonance peak attributed to oscillations of the domain wall, the intensity of which is comparable to the intensity of the peak corresponding to the quasi-homogeneous mode. However, upon application of an alternating magnetic field along the *x* axis, this peak almost completely disappears (Fig. 8b). This makes the use of resonant oscillations of domain walls promising from the point of view of the implementation of tunable microwave filters operating in the frequency range of approximately 1 GHz.

4. CONCLUSIONS

Thus, it was found that the magnetostatic interaction results in a transformation of the ferromagnetic resonance spectrum of a system of interacting microstrip. The noncollinearity of the distribution of the magnetic moment in the systems under investigation gives rise to the possibility of the excitation of not only in-phase oscillations but also out-of-phase coupled oscillations in response to an external uniform microwave magnetic field. In the systems of exchange-coupled microstrips, the interaction between the particles leads to a splitting of the quasi-homogeneous precession modes and to the appearance of additional peaks due to the formation of domain walls. The character of the magnetization distributions in domain walls has an influence both on the position of the corresponding resonance peaks and on the resonance excitation efficiency depending on the direction of the microwave magnetic field. It was demonstrated that the spectrum of microwave radiation absorption by these systems depends substantially on the magnetization configuration, the angle between the microstrips, and the orientation with respect to the alternating magnetic field.

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