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Spin-wave resonance of exchange-coupled three-layers FeNi/Cu/FeNi planar structures

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The spectrums of standing exchange spin waves into magnetic sandwich $Ni_{80}Fe_{20}/Cu(t_{Cu})/Ni_{80}Fe_{20}$ were studied by spin-wave resonance method. The layer of diamagnetic Cu depending on its thickness t_{Cu} provided both positive and negative exchange interaction between ferromagnetic layers. It was shown that spin waves modes of SWR spectra which are described by well-known relation $H^{ac}_{res}(n) \sim n^2$ are standing acoustic exchange spin oscillations of individual ferromagnetic layers, regardless of a sign of interlayer exchange couple. It was detected that spin modes which are optical satellites of acoustic SWR peaks are described by the dependence of the resonance field $H^{op}_{res}(n) \sim n^{5/2}$ or $H^{op}_{res}(n) \sim n^2$ depending on the boundary conditions established on inner interfaces.

Keywords: spin-wave resonance, surface anisotropy constant, exchange interaction constant, interlayer exchange interaction.

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1. Introduction

Interlayer exchange interaction between ferromagnetic layers, divided with (dia-, para)magnetic layer, is a key factor of many properties and physical effects, observed in artificial structures $[\text{ferro}/(\text{dia-},\text{para})]_N$ for the third decade already [1–3]. Value and sign of exchange interaction depend on thickness of „non-magnetic" layer. These characteristics are experimentally defined using statistic and dynamic methods (magnetization curves and FMR). Magnetization curves, beside layers exchange interaction, are also significantly influenced by such additional parameters as uniaxial anisotropy of ferromagnetic layers, surface anisotropy, defined with interface structure, and many more, depending on atomic structure of magnetic layer, controlled by artificial structures formation technology.

Ferromagnetic resonance (FMR) method for studying the interaction of exchange-coupled planar structures compared to others (hysteresis loop oscillography method [4], or using magnetooptical methods (Kerr effect) [5], Brillouin–Mandelstam light scattering (BMLS) [1]) turned out to be the simplest both in application and interpretation of experimental results [6,7]. The obvious advantage of FMR method is the fact, that registered microwave spectrum allows to simultaneously record value and sign of exchange interaction.

Dispersion relation for homogeneous modes, excited in exchange-coupled system with composition of „ferromagnetic"/„non-magnetic layer"/„ferromagnetic", is presented in [2,6,8]. The result of its examination is a conclusion on presence of only two resonance frequencies (two normal modes) at the specified field. Thus, microwave spectrum of such system contains two peaks — acoustic and optical. Acoustic mode corresponds to high-frequency components of two magnetization vectors, resonating in a phase (its field coordinate is defined by internal field). Optical mode corresponds to high-frequency components of two magnetization vectors, resonating in a reversed phase. Exchange energy between individual ferromagnetic layers is accounted by introduction of additional field H_E, that causes displacement of resonance fields (frequencies) of acoustic and optical peaks. The mutual position of the peaks makes it possible to determine the type of magnetization vectors alignment in neighboring layers — ferromagnetic or antiferromagnetic. In the first case the value of interlayer exchange interaction J_{12} is positive, while optical mode is observed in lower fields than the acoustic mode. In the second case, at $J_{12} < 0$, the optical mode is observed at higher fields than the acoustic mode. Using known values of resonance fields of FMR spectrum of acoustic and optical modes the value and sign of interlayer exchange interaction are defined with high accuracy for planar systems with ferro- or antiferromagnetic coupling [8–13]. It should be noted, that there may be planar compositions, at which only acoustic modes (one or two), will be observed in three-layer films spectrum [14–16]. In this case the value of H_E is defined as per coordinate of homogeneous FMR using methods, similar to techniques of H_E deriving from magnetization curves.

Thus, in theoretical calculations of dispersion relations for homogeneous modes and in experimental studies the main requirement is the following: homogeneous FMR, i.e. dynamic magnetization as a response to homogeneous electromagnetic field, is homogeneous ($\overline{m}(0)$), the internal field H_{eff} is also homogeneous in motion equation for $\overline{m}(0)$. Therefore, in planar sandwiches the thicknesses of individual magnetic layers are limited ($3-10$ nm), where lower limit is caused by a condition of individual layer uniformity, while upper limit — by a condition of internal field homogeneity. At the same time, it is known, that in artificial structures with ultrathin layers at normal orientation of external field as relating to film plane, the heterogeneous FMR is observed during experiment, i.e. here both internal field H_{eff} and dynamic magnetization become heterogeneous. Therefore, for planar sandwiches two things are relevant: critical thickness of individual ferromagnetic layer, at which the homogeneous FMR transitions into heterogeneous FMR (particularly, to spin-wave resonance spectrum). And the second thing — if in individual ferromagnetic layer the conditions for SWR excitation are implemented, how is this spectrum modified by exchange interaction with the second magnetic layer'

Also the task of establishing the type of dispersion relation of exchange spin waves for acoustic and optical modes in SWR spectrum, as well as those parameters, that cause its modification, is considered interesting and relevant for us.

We should note the works with registered compound microwave spectra of exchange-coupled three-layer films in perpendicular geometry of the experiment [17–21]; it should be noted, that in [20,21] the heterogeneous FMR is identified as SWR spectrum, where intensive observed peaks are acoustic SWR modes, accompanied by optical satellites. Established in [20,21] original fact of non-quadratic dependence $H_{res}(n)$ of optical satellites of exchange spin-wave modes raised several new questions: if these modifications of dispersion relation are the permanent property of optical modes, and if other power dependences are possible, what parameter defines degree of *n*.

Taking into account, that the results of the works [20,21] were obtained for films at symmetric boundary conditions and with magnetization fixation on a surface of „easy axis" type, we synthesized new samples of planar structures with ferromagnetic and antiferromagnetic exchange coupling at other boundary conditions of exchange spin waves fixation on surface.

2. Sample acquisition and experiment procedure

Three-layer films of $Fe_{20}Ni_{80}/Cu/Fe_{20}Ni_{80}$ with ferromagnetic layers with the same thickness (from 50 to 110 nm) and thickness of non-magnetic layer in a range from 0.8 to 8 nm were obtained using method of thermal evaporation in vacuum of 10^{-6} mm Hg by successive evaporation of layers of $Fe_{20}Ni_{80}$ and Cu from independent evaporators with ring cathode on a glass substrate. Rate of evaporation of FeNi and Cu layers was 0.5 and 0.2 nm/s respectively. Chemical composition and thickness of obtained layers were controlled using X-ray fluorescence analysis.

Microwave spectra of films were made using equipment of the Krasnoyarsk Regional Center of Research Equipment of Federal Research Center — Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences' (spectrometer ELEXSYS E580, Bruker, Germany). Measurement of microwave spectra was performed at room temperature in X-range (resonator excitation frequency is $f = 9.2$ GHz), the sample was put into antinode of variable magnetic field $h_\sim$ of cavity resonator. Measurements were performed at change of direction of permanent magnetic field **H** in the plane, parallel to the film normal (by angle θ_H) (Fig. 1, *a*).

Structure of spectra of SWR systems with composition of „ferromagnetic"/„non-magnetic layer"/„ferromagnetic" is defined by several conditions: presence or absence of interaction between layers [7,22,23]; formation of standing spin exchange wave either in each individual layer or within the whole magnetic system [21]; and effects, appearing at interface, and boundary conditions [24–26]. Positions of resonance fields of individual modes in spectrum of microwave absorption by homogeneous thin film depending on experiment geometry are defined [27,28]:

$$\left(\frac{\omega}{\gamma}\right)^2 = H(H + H_{\text{eff}}) \quad (\text{at } \theta_H = 90^\circ), \tag{1}$$

$$H_n = \frac{\omega}{\gamma} + H_{\text{eff}} - \eta_{\text{eff}} k_n^2 \quad (\text{at } \theta_H = 0^\circ),$$

where $\omega = 2\pi f$ — cyclic frequency [c^{-1}]; $\gamma = 1.758 \cdot 10^7$ [Hz/Oe] — gyromagnetic ratio; $\eta_{\text{eff}} = 2A/M_S$ — spin-wave stiffness [$\text{Oe} \cdot \text{cm}^2$], related to exchange interaction constant A [erg/cm], M_S — saturation magnetization [G], k — wave vector [m^{-1}], H_{eff} — effective field, considering anisotropy influence from various sources, generally $H_{\text{eff}} = 4\pi M_{\text{eff}}$.

As was already mentioned above, one of the important factors, defining the shape of microwave absorption spectrum, are boundary conditions, characterizing with value of surface anisotropy constant K_S and type of surface fixation of dynamic magnetization („easy axis" or „easy plane"). Kittel [28] examined the case of symmetric boundary conditions in a film with thickness L with $K_S = \infty$ on each surface, the permitted values of wave vector $k = \pi n/L$ (where n — number of trigonometric mode, taking the values of $1, 3, 5, 7, \ldots$), while SWR spectrum curve is presented by standing volume spin odd modes only. Generally on various film surfaces the spins are fixated differently, resulting in implementation of boundary conditions ($K_{S1} \neq K_{S2}$) and creates possibility for excitation

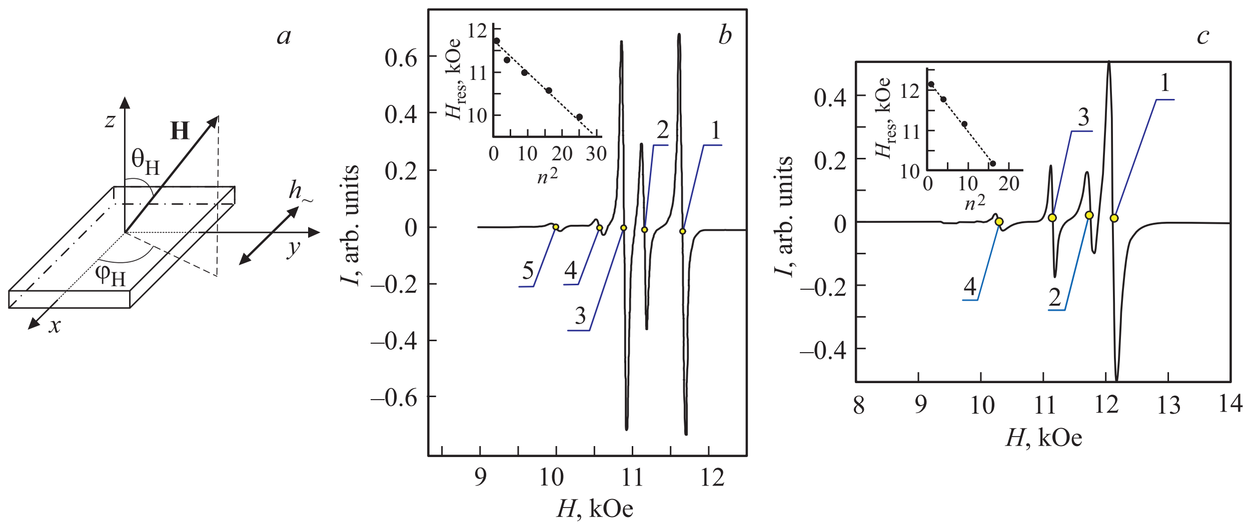

Figure 1. (a) — geometry of measurements performing and examples of SWR spectra at $\theta_H = 0^\circ$ of single-layer FeNi film with thickness of ~ 117 nm (b) and film of NiFe(~ 126 nm)/Cu(~ 17 nm) (c) (numbers in figure indicate numbers of volume standing modes). Dependencies of $H_{res}(n^2)$ are presented in inserts of spectra.

Table 1. Magnetic characteristics of reference samples

Sample	M_{eff}, G	A, 10^{-6} erg/cm
NiFe($\sim$ 126 nm)/Cu($\sim$ 17 nm)	715	0.695
NiFe($\sim$ 117 nm)	690	0.59
NiFe($\sim$ 95 nm)	650	0.52
Cu($\sim$ 16 nm)/NiFe($\sim$ 82 nm)/Cu($\sim$ 16 nm)	744	0.58

of even modes (see Fig. 1, *b* and *c*). When the hard axis of surface anisotropy is normal to the film surface at least on one surface (fixation type — „easy plane“ and $K_S < 0$), registration of hyperbolic non-propagating exchange spin wave (surface mode) with imaginary wave vector is possible in SWR spectrum [24–26,29].

Presence of surface modes in spectrum allows to directly measure the value of surface anisotropy constant, that (when $K_S < 0$) is calculated as per formula

$$|K_S| = \left[\frac{M_S \cdot A}{2}\left[(H_S - H_1) - \frac{2A}{M_S}\left(\frac{\pi}{L}\right)^2\right]\right]^{1/2}. \quad (2)$$

SWR spectra at boundary conditions with „easy axis“ fixation type ($K_S > 0$) do not contain surface modes, but value of surface fixation constant can be evaluated from expression [30]:

$$K_S = n^2\pi \frac{A}{L}\frac{\Delta H_n}{\Delta H_1}\sqrt{\frac{I_n}{I_1}}, \quad (3)$$

where ΔH_n and I_n — line width and intensity of n-th volume standing spin mode, ΔH_1 and I_1 — line width and intensity of the first mode.

Identification of SWR spectra of three-layer films was performed considering parameters, defined from reference samples. Synthesized to glass substrates, the single-layer reference films of $Fe_{20}Ni_{80}$ allowed to define the effective magnetization M_{eff} and exchange interaction constant A (Table 1) from microwave absorption spectra (Fig. 1, *b*) and expression (1). Presence of mode with $n = 2$ in spectrum and absence of surface peak indicate the implementation of approximate symmetric boundary conditions with „easy axis“ fixation type. Positions of resonance fields H_{res} from mode number n at $\theta_H = 0^\circ$ are well described with expression (1) (see insert in Fig. 1, *b*): $H_{res} \sim n^2$. The same quadratic dependence of H_{res} on n also remains for films with composition of NiFe/Cu and Cu/NiFe/Cu, which were synthesized for evaluation of copper layer influence on magnetic parameters of three-layer system, including boundary conditions. SWR spectrum of two-layer film of NiFe($\sim$ 126 nm)/Cu($\sim$ 17 nm) is presented in Fig. 1, *c*.

Values of effective magnetization and exchange interaction constants for reference films, defined from FMR and SWR spectra, are presented in Table 1.

Presence of exchange coupling between ferromagnetic layers, separated by a nonmagnetic layer and with difference in magnetic parameters, creates condition for

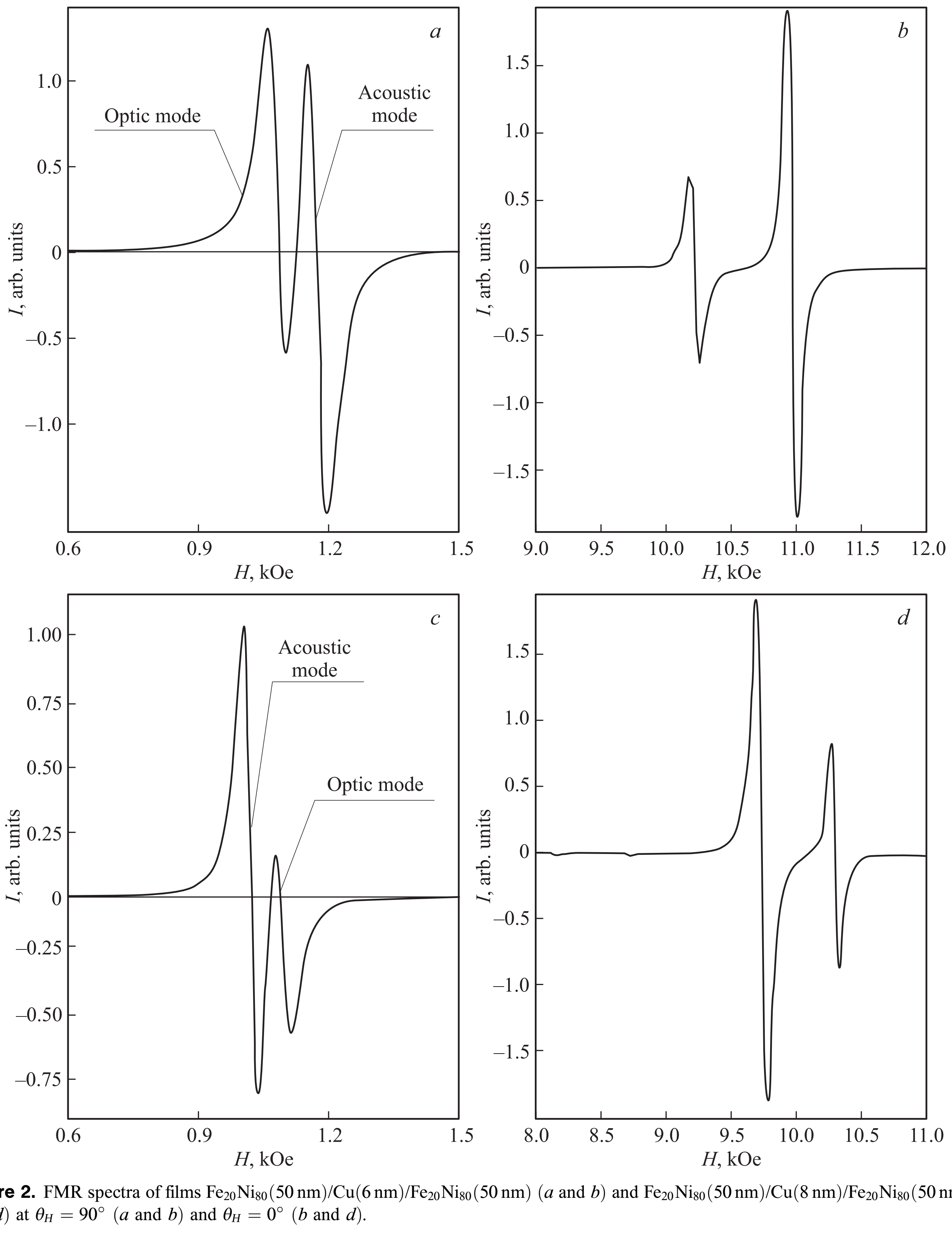

Figure 2. FMR spectra of films $Fe_{20}Ni_{80}(50\,\text{nm})/Cu(6\,\text{nm})/Fe_{20}Ni_{80}(50\,\text{nm})$ (*a* and *b*) and $Fe_{20}Ni_{80}(50\,\text{nm})/Cu(8\,\text{nm})/Fe_{20}Ni_{80}(50\,\text{nm})$ (*c* and *d*) at $\theta_H = 90^\circ$ (*a* and *b*) and $\theta_H = 0^\circ$ (*b* and *d*).

excitation in the microwave absorption spectrum along with acoustic mode of optical mode, intense enough for its registration regardless of the orientation of the constant and high-frequency field [7]. Mutual position of these two peaks in FMR spectrum of films of $Fe_{20}Ni_{80}(50\,\text{nm})/Cu(t_{Cu})/Fe_{20}Ni_{80}(50\,\text{nm})$ (spectra examples are in Fig. 2) allowed to define the value of interlayer exchange interaction J_{12} and its sign $\left(|H_E| = 2J_{12}/(M_S L)\right)$.

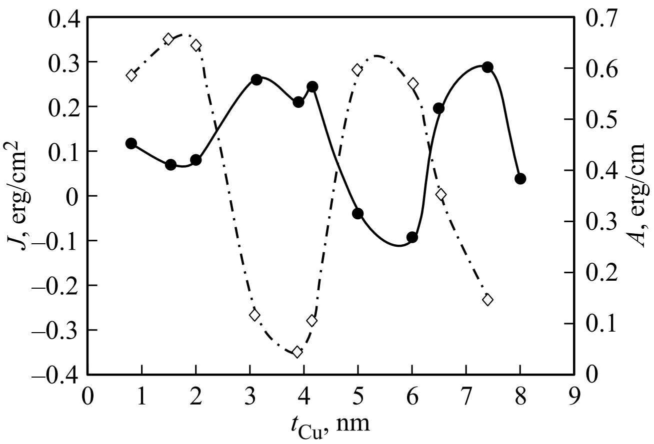

Figure 3. Dependencies of values of exchange interaction of ferromagnetic layers J_{12} (dashed line) and exchange interaction constants for exchange spin waves (solid line) on copper layer thickness [20].

Dependence of J_{12} on thickness of Cu layer t_{Cu} for three-layer systems $Fe_{20}Ni_{80}(50\,\mathrm{nm})/Cu(t_{\mathrm{Cu}})/Fe_{20}Ni_{80}(50\,\mathrm{nm})$ from FMR spectra ($\theta_H = 90^\circ$) was established in [20] (see Fig. 3). Also in [20] the results of microwave absorption spectra measurement were presented at $\theta_H = 0^\circ$ for sandwiches of $Fe_{20}Ni_{80}(70\,\mathrm{nm})/Cu/Fe_{20}Ni_{80}(70\,\mathrm{nm})$, individual peaks in which were identified as standing exchange spin acoustic and optical modes. The registered SWR spectra allowed to establish, first of all, the type of dependence of resonance fields positions H_{res} of spin-wave modes on mode number n: for acoustic modes — $H_{res}^{ac} \sim n^2$, for optical — $H_{res}^{op} \sim n^{5/2}$. Secondly, the dependence of value of exchange interaction constant A, calculated from (1) as

$$\frac{1}{2} M_S (L/\pi)^2 \left[(H_n - H_{n+1}) / \left((n+1)^2 - n^2\right)\right]$$

on t_{Cu} (Fig. 3).

Using dependence of $J(t_{\mathrm{Cu}})$, presented in Fig. 3, the thickness of Cu layer was selected for implementation of both ferromagnetic and antiferromagnetic exchange coupling. The observed films were synthesized with compositions:

$Fe_{20}Ni_{80}(74)/Cu(0.8)/Fe_{20}Ni_{80}(74)$,

$Fe_{20}Ni_{80}(74)/Cu(3.6)/Fe_{20}Ni_{80}(74)$,

$Fe_{20}Ni_{80}(95)/Cu(7.5)/Fe_{20}Ni_{80}(95)$ and

$Fe_{20}Ni_{80}(106)/Cu(7.8)/Fe_{20}Ni_{80}(106)$,

numbers in parentheses indicate layer thickness in nm.

3. Results and discussion

Synthesized films had various boundary conditions: at both boundaries of standing spin waves fixation $K_S > 0$ (symmetric conditions); at one of the boundaries $K_S > 0$, at another $K_S < 0$ (at modules equality — antisymmetric conditions); at both boundaries of fixation $K_S < 0$ (symmetric conditions). Experimental spectra of microwave absorption at $\theta_H = 0^\circ$ are presented in Fig. 4.

The registered SWR spectra have complicated view, presented by many modes (Fig. 4), their identification was performed based on condition of optical satellite excitation near each acoustic peak and assumption, that normal modes are described with a single, but unknown law $H_n^i = f_i(n)$. Modes numbers were introduced as per acoustic peaks according to rules, described in [24,25,29,31–33], considering such parameters as intensity, implemented boundary conditions, magnetic layer thickness. Individual modes in the registered spectra were singled out through breakdown using differentiated Lorentz function (Fig. 4, *c* and *d*). Selection of Lorentz function considered absence of electrical element contribution (caused by resonator design and sample sizes).

Determination of type of exchange interaction and numbering of individual spectrum peaks at $\theta_H = 0^\circ$ were performed considering dependence $J_{12}(t_{\mathrm{Cu}})$, as well as angular dependencies $H_{res}(\theta_H)$. Example of one of the angular dependencies for film of $Fe_{20}Ni_{80}(106\,\mathrm{nm})/Cu(7.8)/Fe_{20}Ni_{80}(106\,\mathrm{nm})$ is presented in Fig. 5, *a*. Experimental values of resonance fields of acoustic H_{res}^{ac} and optical H_{res}^{op} modes in angular range of $10 < \theta_H < 90^\circ$ are described with relation $H_{res}^{ac} > H_{res}^{op}$, indicating the ferromagnetic interlayer exchange interaction [7].

Determination of values A and K_S from SWR spectra at $\theta_H = 0^\circ$ was performed considering displacement of fixation nodes of the standing exchange spin wave from geometrical boundaries inside ferromagnetic layer [20,34–37].

The model, presented in Fig. 5, *b*, assumes that standing waves at $\theta_H = 0^\circ$ are excited in each individual layer, the confirmation of that is similarity of values of M_{eff} and A of a reference single-layer film of permalloy and three-layer film of NiFe($\sim 100\,\mathrm{nm}$)/Cu($\sim 6.5\,\mathrm{nm}$)/NiFe($\sim 100\,\mathrm{nm}$) ($M_{\mathrm{eff}} \approx 630\,\mathrm{G}$, $A \approx 0.52 \cdot 10^{-6}\,\mathrm{erg/cm}$) with $J_{12} \approx 0$, in spectrum of which only acoustic modes are excited (Fig. 6) and $H_{res} \sim n^2$.

Dependencies of resonance fields H_{res} of individual peaks on mode number n for films, which spectra are demonstrated in Fig. 4, are presented in Fig. 7.

Acoustic modes for all films at any boundary conditions with reasonable accuracy are described with dependence $H_{res}^{ac}(n) \sim n^2$ (Fig. 7). Dependences of resonance fields on mode number of optical modes are different and defined by boundary conditions. SWR spectra of films with t_{Cu} 0.8 and 3.6 nm (Fig. 4, *a* and *b*) are presented with volume standing modes only, therefore at each boundary of these structures — air/FeNi, FeNi/Cu, Cu/FeNi and FeNi/substrate, the fixation conditions of „easy axis“ type with $K_{\mathrm{Si}} > 0$ are implemented. Dependencies $H_{res}^{op}(n)$ for these films are proportional to $n^{5/2}$ (Fig. 7, *a* and *b*). SWR spectra of films with t_{Cu} 7.5 and 7.8 nm (Fig. 4, *c* and *d*) contain surface modes,

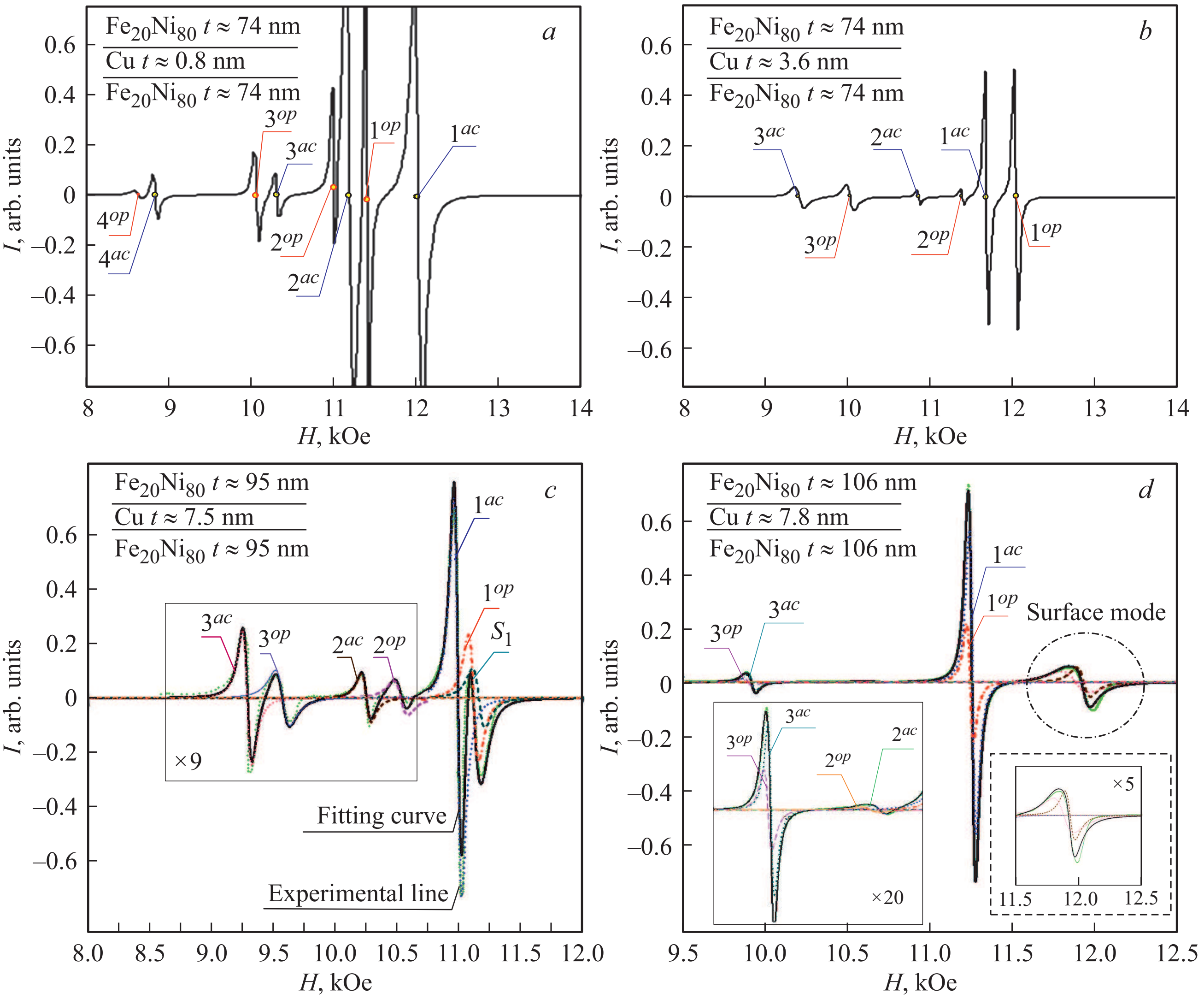

Figure 4. SWR spectra of three-layer films of $Fe_{20}Ni_{80}/Cu/Fe_{20}Ni_{80}$ at $K_{Si} > 0$ at boundaries of standing spin waves fixation (*a* and *b*); when at one internal interface $K_S > 0$, and at another $K_S < 0$ (*c*); and at $K_S < 0$ at both internal boundaries of standing spin waves fixation (*d*).

therefore the conditions of boundary fixation of „easy plane“ type are implemented and dependencies of resonance fields of optical modes on mode number change its form — $H^{op}_{res}(n) \sim n^2$ (Fig. 7, *c* and *d*). Taking into account SWR spectra of reference single-layer films (Fig. 1, *b* and *c*), in which there were no surface modes (i.e. at interfaces „air/FeNi“ and „FeNi/substrate“ $K_{Si} > 0$), the registered surface modes in films with t_{Cu} 7.5 and 7.8 nm are conditioned by fixation type of dynamic magnetic moment at internal interfaces of three-layer structures.

Spin wave, having dual nature, can be described not only as magnetization wave in magnetically ordered substances, but also as a particle — magnon. Examining the phenomena, observed in the studied films, from the perspective of corpuscular nature of spin wave the analogies can be made between magnon and electron, for which there are various solutions of dispersion relation, describing the stationary states at various conditions.

Considering non-magnetic layer between two ferromagnetic layers, the most appropriate are conclusions, made for the case of potential box with semi-permeable membrane. Stationary states in this case are divided into two classes — with positive and negative parity, and each class of tasks corresponds to its expression, defining the wave vector k. At positive parity and width of potential box a

$$k\,\mathrm{ctg}(ka) = -\Omega, \tag{4}$$

then

$$\left(n - \frac{1}{2}\right)\pi < k_n a < n\pi. \tag{5}$$

Thus, the values of the wave vector are defined with partition impermeability coefficient Ω.

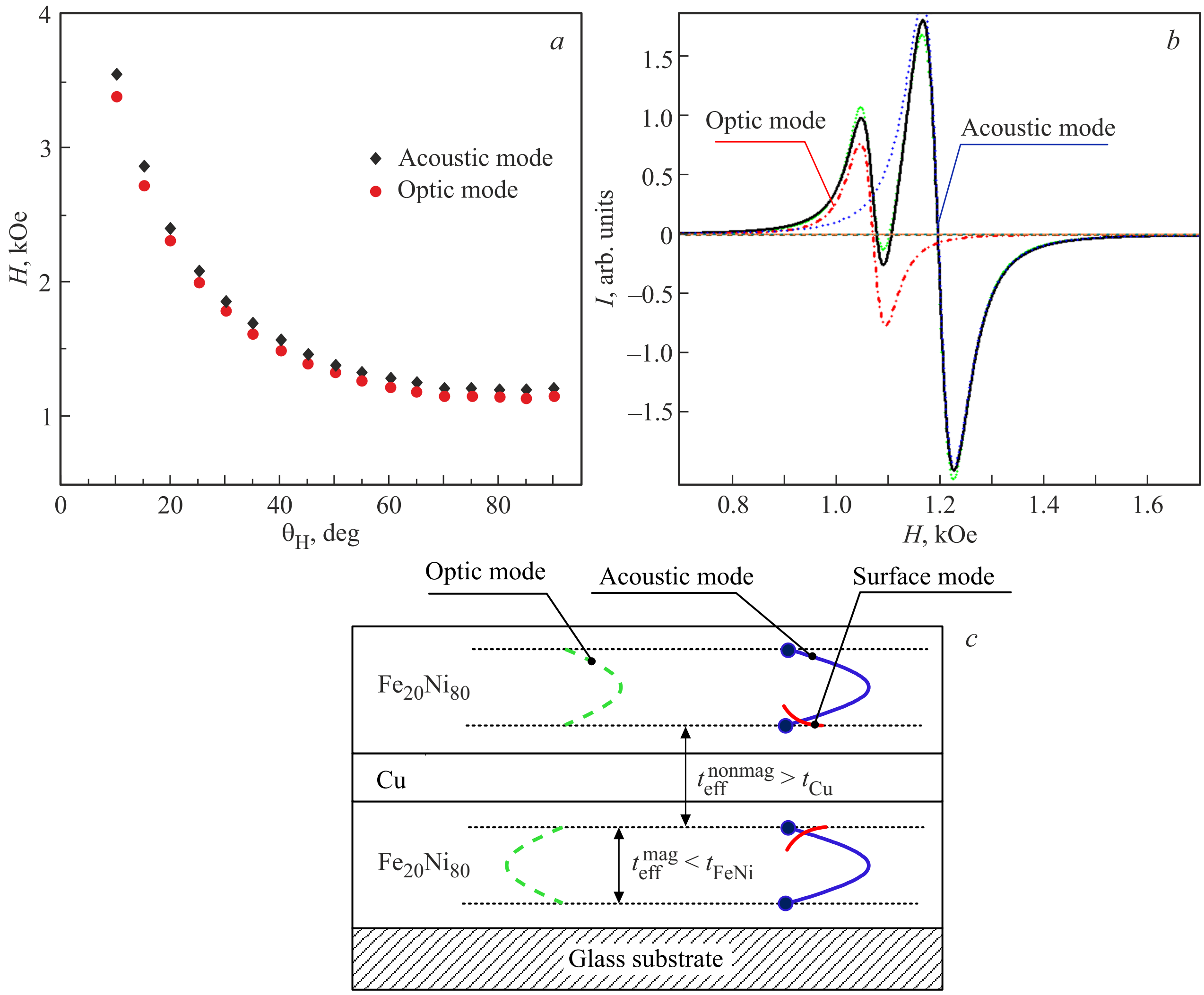

Figure 5. Angular dependence of values of H_{res}^{ac} and H_{res}^{op} (a) and example of microwave absorption spectrum at $\theta_H = 90°$ of the film of $Fe_{20}Ni_{80}(106)/Cu(7.8)/Fe_{20}Ni_{80}(106)$ (b), and model of spin standing modes distribution at $\theta_H = 0°$ (b).

At negative parity

$$ka = n\pi. \quad (6)$$

Wave vectors of spin waves, excited in a film with thickness L at $K_S > 0$ on each surface, are also defined with two expressions [29] for antisymmetric solutions

$$k\,\mathrm{ctg}(kL) = -\frac{K_S}{A} \quad (7)$$

and symmetric solutions

$$Lk = n\pi. \quad (8)$$

It should be noted, that expression (8) is also true at different (both by sign and value) values of K_S on each surface of the standing wave node fixation.

It is seen, that expressions (4) and (7), as well as (6) and (8) are similar. Then, the implementation of acoustic modes in exchange-coupled films can be described as

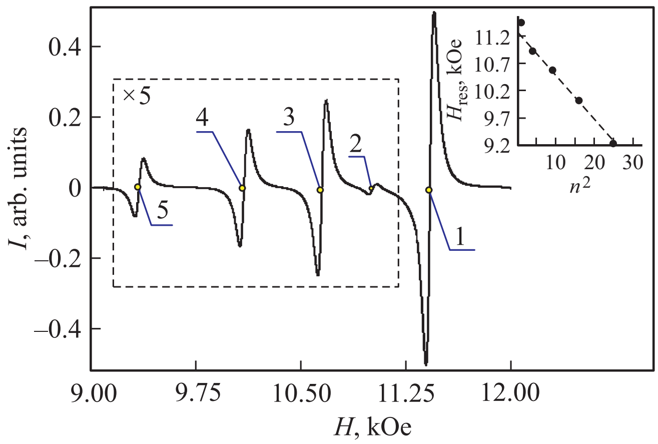

Figure 6. SWR spectrum of the film of NiFe(∼ 100 nm)/Cu(∼ 6.5 nm)/NiFe(∼ 100 nm); insert shows dependencies of resonance fields positions on square of mode number.

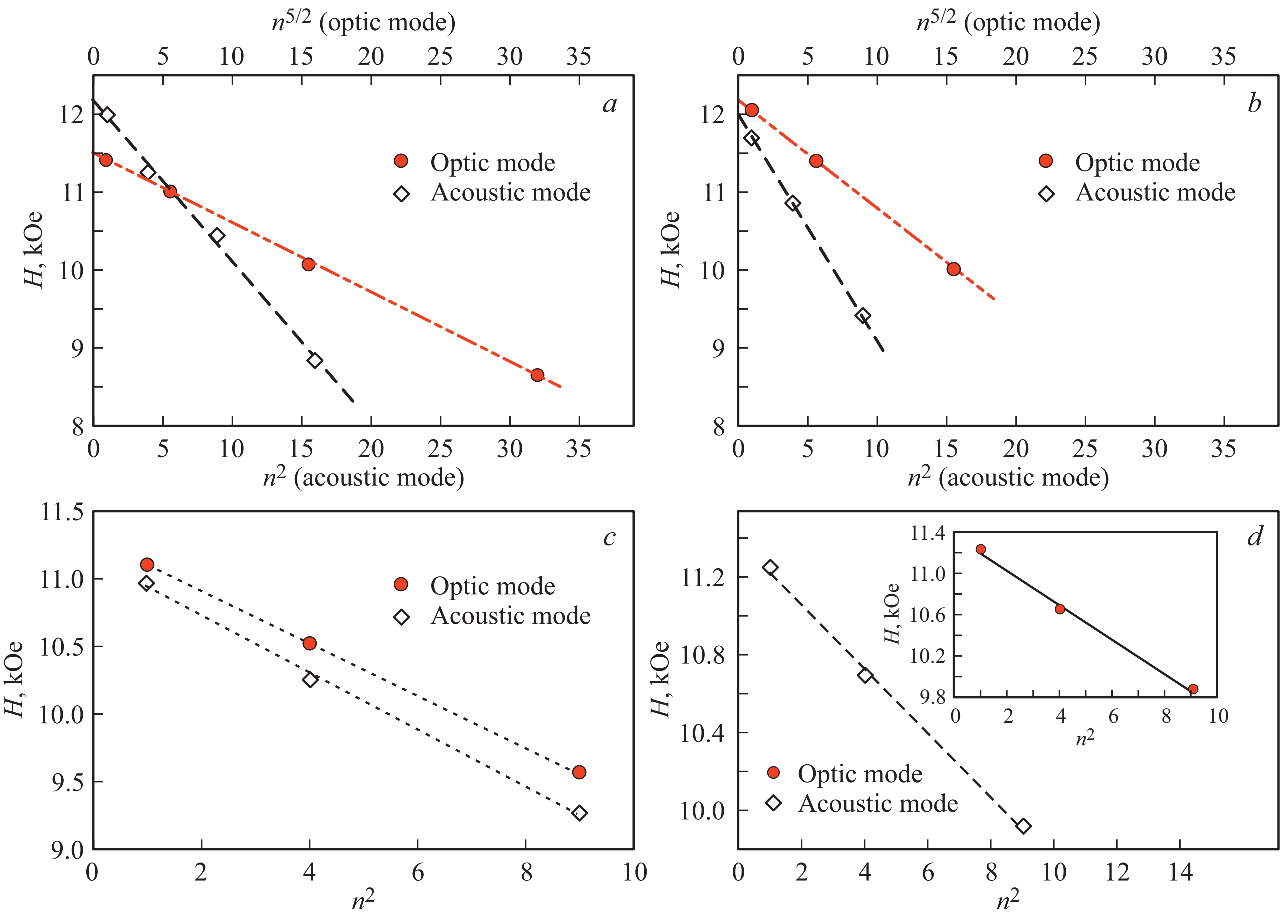

Figure 7. Dependencies $H_{res}(n)$ for films of $Fe_{20}Ni_{80}/Cu/Fe_{20}Ni_{80}$ with t_{Cu} 0.8 (*a*), 3.6 (*b*), 7.5 (*c*) and 7.8 nm (*d*).

Table 2. Magnetic parameters of three-layer films

Thickness of Cu layer	0.8 nm	3.6 nm	7.5 nm	7.8 m
Type of fixation at internal surface	„easy axis“		„easy axis“ and „easy plane“	„easy plane“
Dependence type $H_{res}(n)$				
for acoustic modes	$H^{ac}_{res}(n) \sim n^2$		$H^{ac}_{res}(n) \sim n^2$	$H^{ac}_{res}(n) \sim n^2$
for optical modes	$H^{op}_{res}(n) \sim n^{5/2}$		$H^{op}_{res}(n) \sim n^2$	$H^{op}_{res}(n) \sim n^2$
$M_{\rm eff}$, G	~ 716	~ 694	~ 660	~ 620
A, 10^{-6} erg/cm	~ 0.42	~ 0.58	~ 0.5	~ 0.53
K_S, erg/cm^2	~ 0.07	~ 0.13	~ 0.027	~ 0.22

solutions for stationary states of electron at negative parity, when wave vector is described with (6), and thus in SWR spectra the dependence of positions of acoustic peaks resonance fields on mode number is quadratic at any boundary conditions (Figs 4 and 7). Optical modes are described with wave vectors, which are defined with expression (7), and similar to the expression (5) the wave vector k of optical modes at $K_{\rm Si} > 0$ can take values in a wide range, and that will be manifested in SWR spectrum as deviation of $H^{op}_{res}(n)$ from quadratic law (Fig. 7, *a* and *b*). Deviation ratio is defined with a value of surface fixation constant K_S, as per equality of the right parts of expressions (4) and (7).

The main magnetic parameters of the examined three-layer exchange-coupled films, defined from expressions (1)–(3), as well as abovementioned criteria of SWR spectra identification, are presented in Table 2. Values of K_S were evaluated as per acoustic peaks.

Determination of surface anisotropy constant for films with symmetric boundary conditions was also performed from optical modes position as per (7). K_S for film with thickness of Cu layer of $t_{\mathrm{Cu}} = 0.8$ nm was $\sim 0.06\,\mathrm{erg/cm^2}$, and at $t_{\mathrm{Cu}} = 3.6$ nm, $K_S \sim 0.08\,\mathrm{erg/cm^2}$, the observed values are in acceptable agreement with similar ones, presented in Table 2.

4. Conclusion

Measurements, performed using dynamic methods of magnetic characteristics of three-layer exchange-coupled films, allowed to define not only values of fundamental magnetic parameters — effective magnetization, exchange interaction constant from exchange spin wave spectrum, surface anisotropy constant and value and sign of interlayer exchange J_{12}. They also allowed to make the following conclusions. First of all, in planar sandwich of NiFe/Cu/NiFe at ferromagnetic layers thickness of $L \approx 40-60$ nm in two geometries of the experiment (parallel and orthogonal orientation of external field) the spectrum of homogeneous FMR of two normal modes (acoustic and optical) is observed.

In planar sandwich of NiFe/Cu/NiFe at individual magnetic layers thicknesses of $L \approx 70-110$ nm in orthogonal geometry of the experiment the heterogeneous FMR (SWR spectrum) is observed. Therefore, the critical thickness of individual ferromagnetic layer in our case is $L_{\mathrm{crit.}} \approx 70$ nm.

Secondly, it was established, that in SWR spectrum of planar sandwiches the boundary conditions impact the functional dependence of resonance fields on mode number. Thus, field coordinates of „acoustic" peaks of SWR at any boundary conditions are quadratic from mode number — the law of $H_{res}^{ac} \sim n^2$ is implemented. Positions of resonance fields of optical modes at symmetric boundary conditions are described with dependence of $H_{res}^{op}(n) \sim n^{5/2}$ type, at antisymmetric — $H_{res}^{op}(n) \sim n^2$. Deviation from quadratic dependence is defined with a value of surface fixation constant.

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Conflict of interest

The authors declare that they have no conflict of interest.

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