Izvestiya Vysshikh Uchebnykh Zavedeniy. Applied Nonlinear Dynamics. 2022;30(5)

Review DOI: 10.18500/0869-6632-2022-30-5-534-548

Resonant and nonlinear phenomena during the propagation of magnetostatic waves in multiferroid, semiconductor and metallized structures based on ferromagnetic films and magnon crystals

M. A. Morozova✉, *O. V. Matveev*

Saratov State University, Russia
E-mail: ✉mamorozovama@yandex.ru, olvmatveev@gmail.com
Received 4.06.2022, accepted 23.06.2022, published 30.09.2022

Abstract. *Purpose* of this work is to compile an overview of a new and fruitful scientific direction in magnons, which grew out of the works of Ph.D., Professor Yuri Pavlovich Sharaevsky, and related to the study of resonant and nonlinear phenomena during the propagation of magnetostatic waves in ferromagnetic films, ferromagnetic films with periodic inhomogeneities (magnon crystals), coupled (layered and lateral) ferromagnetic structures, as well as ferromagnetic structures with layers of a different physical nature (semiconductor, ferroelectric, piezoelectric, normal metal layers). *Methods.* Experimental and theoretical methods have been used to study spin-wave excitations in a wide class of structures with ferromagnetic layers. In particular, experimental radiophysical methods of microwave measurements and optical methods of Mandelstam-Brillouin spectroscopy. For the construction of theoretical models, the following methods are used: the method of coupled waves, the method of crosslinking magnetic permeability at the boundaries of layers, the method of transmission matrices, long-wave approximation. *Results.* The presented results are of general scientific importance for understanding the basic laws of the joint influence of coupling, periodicity and interactions of different physical nature (the influence on the magnetostatic wave of deformation in periodic structures with piezoelectric, electromagnetic wave in structures with ferroelectric, electric current in structures with semiconductor, spin current in structures with normal metal). In applied terms, the identified effects open up wide opportunities for creation of new devices of spin-wave electronics with the possibility of dynamic control of characteristics when changing the electric and magnetic fields, as well as the power of the input signal. *Conclusions.* The review of the most interesting results obtained by the authors together with Yuri Pavlovich and which are an ideological continuation of the foundations laid by him is given.

Keywords: ferromagnetic film, magnetostatic wave, magnon crystal, semiconductor, ferroelectric, piezoelectric, normal metal.

Acknowledgements. This work was supported by Russian Science Foundation, grant №19-79-20121 (experimental studies) and Russian Foundation for Basic Research, grant №19-29-03049-mk (theoretical studies).

For citation: Morozova MA, Matveev OV. Resonant and nonlinear phenomena during the propagation of magnetostatic waves in multiferroid, semiconductor and metallized structures based on ferromagnetic films and magnon crystals. Izvestiya VUZ. Applied Nonlinear Dynamics. 2022;30(5):534–553. DOI: 10.18500/0869-6632-2022-30-5-534-548

Introduction

This article provides a brief overview of a new and fruitful scientific direction in magnons, which grew out of the works of Yuri Pavlovich Sharaevsky. It is connected with the research of resonant and nonlinear phenomena during the propagation of magnetostatic waves in ferromagnetic films, ferromagnetic films with periodic inhomogeneities (magnon crystals), coupled (layered and lateral) ferromagnetic structures, as well as ferromagnetic structures with layers of other physical nature (semiconductor, ferroelectric, piezoelectric, layers of normal metal). In a widely known monograph «Magnetostatic waves in microwave electronics» [1] by Vashkovsky A. V., Stalmakhov V. S., Sharaevsky Yu. laid the foundation for the development, including this direction, the fundamental laws were obtained, which opened up wide opportunities for the further work of many scientists both in our country and abroad. Almost all the ideas presented in the monograph were further developed, were the impetus for a huge number of important discoveries in this field, made later by both students of Yuri Pavlovich Sharaevsky and in other scientific groups. The authors of the article were lucky enough to study and work with this unique person. For us, Yuri Pavlovich was not only a wise teacher, but also an ideological inspirer. Our path in science was completely determined by close work with this extraordinary scientist, joint long scientific discussions, disputes, the search for truth, and then amazing discoveries. This article provides a selective review of the most interesting, in our opinion, results obtained by the authors together with Yuri Pavlovich and are an ideological continuation of the foundations laid by him.

In recent years, magnonics — a new direction in electronics — has attracted wide attention of researchers. In magnon devices, spin waves [1–5] are used to transmit the signal. Work in this area is extremely relevant, because in the future it will allow us to develop a new generation of devices and appliances for transmitting and processing data, with characteristics that could not have been obtained earlier. Unlike conventional microwave devices, spin-wave or magnon devices have advanced capabilities, thanks to control both by means of an external magnetic field and under influences of a different physical nature (for example, deformations, electromagnetic waves, electric and spin current). Moreover, many semiconductor integrated technologies can be easily combined with devices based on the principles of magnons.

One of the main structures proposed for creating a magnon component base are magnon crystals (MC) — periodic structures based on magnetic materials [6–8]. MC, due to the formation of band gaps (BG) — non-transmission bands in the spectrum of spin waves, are functionally more flexible and have greater capabilities for controlling characteristics, compared with homogeneous magnetic structures. In this case, the task of controlling the characteristics of the band gaps in the spectrum of propagating waves is important. It was proposed to control the characteristics of the band gaps both statically, for example, by changing geometric parameters, changing materials, changing boundary conditions, creating defects, and dynamically, for example, using magnetic and electric fields, creating a temperature gradient, acoustic wave propagation, etc., etc.

The most promising ferromagnetic materials for magnons problems are nano- and microfilms of yttrium iron garnet (YIG) due to extremely low microwave losses and weak magnetic anisotropy [9]. Nonlinear effects in the films of the YIG are manifested at relatively low levels of input power. The main nonlinear effects in the MC in the region of four-magnon decay processes are the nonlinear shift of the band gaps and the formation of Bragg solitons [10, 11].

An alternative way to control the characteristics of BG and nonlinear wave processes in the MC can be the use of loads of different physical nature.

If a second ferromagnetic layer (ferromagnetic film or MC) is used as the load, the structure is a bound ferromagnetic structure. Due to the coupling between magnetic channels, the dynamic properties of wave processes change significantly and new types of spin-wave excitations are realized. Coupled structures significantly expand the functionality of radiophysical systems, as an additional control parameter appears — communication. Studies of coupled ferromagnetic structures are relevant due to the increasing need to combine individual magnon signal processing elements into magnon networks [12, 13].

The magnetic control method can be implemented in a wide frequency range, but the control is relatively slow and requires significant energy consumption. In turn, the electric control method is faster than the magnetic one. To implement electrical control of linear and nonlinear spin-wave excitations, ferromagnetic structures based on homogeneous (non-periodic) ferromagnetic films use loads whose properties can be controlled by applying an electric field. Such loads can be: ferroelectric (FE) and piezoelectric (PE) layers, layers of semiconductor (SC) material, normal metals (NM). The physical mechanisms of the influence of the electric field applied to the load on the character of spin-wave processes in a ferromagnetic film will be different in each case.

In the case of ferrite-ferroelectric multiferroid structures based on a ferromagnetic film and a FE layer, an electromagnetic wave propagating in the FE layer affects the spectral characteristics of spin waves in a ferromagnetic film [14]. Hybrid electromagnetic-spin waves (HEMSW) occur at frequencies close to the frequency of phase synchronism of the electromagnetic wave and the spin wave.

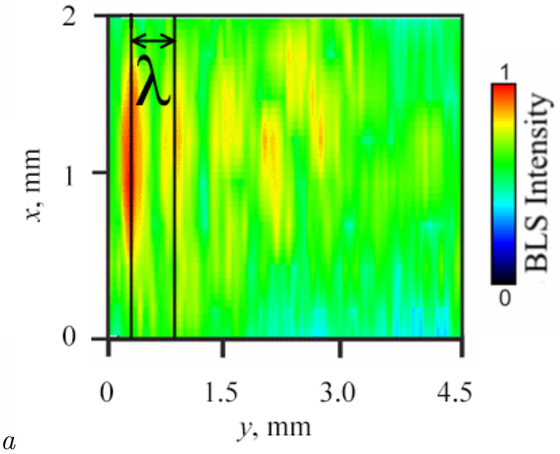
Deformation in a piezoelectric load due to the magnetoelastic effect leads to a change in the internal magnetic field in a ferromagnetic film with magnetostriction. Non-periodic structures of the ferromagnetic film/PE type formed the basis of a new direction of micro- and nanoelectronics — straintronics [15].

Electronic transport in semiconductor loads, due to the action of the Lorentz force, leads to a change in the attenuation and spectral characteristics of spin waves. In periodic ferromagnetic structures with SC-loads, the possibility of creating and suppressing BG in the spectrum of spin waves [16] is theoretically shown. Modern technologies for the development of YIG-semiconductor structures confirm the possibility of integrating CMOS electronics and magnons [17].

Another way to deal with attenuation lies in the field of spintronics (or spin electronics). In spintronics devices, along with the charge, the spin of particles is used, associated with the presence of its own mechanical moment. Spin current in a normal metal, due to the transmission of spin torque at the ferromagnetic film/NM interface, can lead to an increase or decrease in spin waves in the ferromagnetic film [18].

Thus, the problems that are considered in the review and are devoted to the study of linear and nonlinear waves in periodic ferromagnetic structures, as well as in multiferroid structures and heterostructures based on a semiconductor or a normal metal, are important and of considerable scientific interest. The studied structures have both the advantages of periodic structures (formation of band gaps, bragg solitons), the advantages of coupled structures (spatial power transfer), and the advantages of interactions of excitations of different physical nature (the effect on the spin wave of deformation in structures with PE, electromagnetic wave in structures with FE, electric current in structures with SC, spin current in structures with NM). Thus, the structures under study open up new potential possibilities for the functional processing of spin-wave microwave signals that require detailed fundamental research. This allows us to consider the topic of the work relevant for modern radiophysics.

The paper provides a brief overview of new resonant and nonlinear effects in heterostructures based on magnon crystals and layers whose characteristics can be controlled using magnetic and electric fields (ferromagnetic, ferroelectric, piezoelectric, semiconductor, layers based on normal metals), as well as mechanisms of joint influence of coupling, periodicity and interactions of different physical nature, which they will allow efficient control of wave processes for the creation of microwave electronics devices with new functionality based on the principles of magnons.



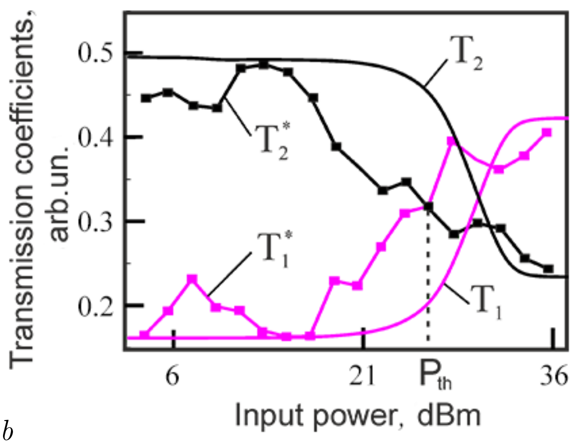


Fig. 1. *a* — The distribution of the intensity of spin waves in the FF-2 at an input power of $P_{\text{in}} = 6$ dBm. *b* — Experimental (point curves) and theoretical (solid curves) dependences of the transmission coefficients for FF-1 (pink curves) and FF-2 (black curves) on the input signal power (color online)

1. Coupled ferromagnetic films

In recent years, coupled ferromagnetic structures have been actively proposed for nanoelectronics and nanoscale magnons, for example, as power dividers, directional couplers, binary logic elements [13, 19]. However, the first steps in the systematization of theoretical and experimental approaches to the study of multilayer ferromagnetic systems are given in [1]. In the future, this direction was also developed (for example, at the SSU under the leadership of Yuri Pavlovich Sharaevsky) in the field of nonlinear dynamics. In particular, a nonlinear wave model is constructed to describe the spin-wave evolution of direct volumetric magnetostatic waves MSDVW and surface MSSW in a coupled ferromagnetic structure. The model is a system of wave equations for the amplitudes of the envelopes of symmetric and antisymmetric waves with linear and nonlinear (coherent or incoherent) coupling. Based on the numerical solution of the wave equations, such nonlinear effects as the capture effect, the tracking effect, nonlinear beats, modulation instability [20–22] are revealed.

In recent years, the intensive development of the experimental base of Saratov University has made it possible to conduct detailed experimental studies of multilayer ferromagnetic structures. Thus, when using the mandelstam–brillouin spectroscopy, which allows us to study the spatiotemporal distribution of the intensity of spin waves in the plane of ferromagnetic microstructures, the effect of suppressing spatial power transfer between the layers of the structure was detected with an increase in the power of the input signal [23].

The structure of ferromagnetic films FP-1/FP-2 (FF-1/FF-2) was formed on the basis of 12 micron thick YIG films separated by a mica plate 50 microns thick. The signal was fed to the input of the FF-1. In Fig. 1, *a* shows a map of the spatial distribution of the intensity of scattered light (proportional to the intensity of the spin wave) obtained using mandelstam-brillouin spectroscopy technology. With a low input power in the FF-2, a pattern of alternating maxima and minima (with a spatial period λ) of intensity along the direction of propagation y is visible, which is explained by the periodic pumping of the signal between the FF-1 and the FF-2. At high power, the periodic distribution of the signal in the films is not observed. Let's choose an observation point at the maximum of the signal in FF-2 at low input power, for example, at a distance of $l = 3\lambda/2$ from the input. At this distance, all the signal that was fed to the FF-1 was pumped to the FF-2. In Fig. 1, *b* shows the dependence of the transmission coefficients of FF-1 and FF-2 on the power of the input signal P_{in}. It can be seen that there is such a threshold power P_{th} at which the transmission coefficients are equal. When the input signal level is above the threshold, most of the power is concentrated in the FF-1. Consequently, there is a pumping suppression effect. Based on the theoretical model, it is shown that the mechanism of the suppression effect is due to an increase in the phase difference between the signals in each film.

2. Magnon Crystals

The appearance of the term «magnon crystal» as a periodic ferromagnetic structure is usually associated with the works of Nikitov S. A. [6, 24]. In the early works of Yu., P.Sharaevsky, studies of ferromagnetic structures with periodic boundary conditions are also reported [1, 25]. Theoretical and experimental studies of magnon crystals were actively conducted on the basis of Saratov University under the leadership of Yuri Pavlovich.

The features of the formation of Bragg band gaps, as well as a number of nonlinear effects, such as nonlinear shift of the band gap and nonlinear switching (between transmission and non-transmission modes of the MC) with increasing input signal power, are investigated. Special attention was paid to such important nonlinear effects as modulation instability and the formation of Bragg solitons. Bragg solitons — are the solitons of the envelope of the spin wave, which are formed due to the effective interaction of the direct and reflected from the inhomogeneities of spin waves at frequencies lying in the band gap in the linear case. The possibility of formation of Bragg solitons in the MC is shown for the first time in the work [26]. At low input power (the purple curve in Fig. 2) the signal is reflected from the MC as from a linear Bragg lattice (pulses 1 and 2 correspond to the front and slice of the input rectangular pulse). With an increase in the input amplitude, the formation of a Bragg soliton takes place (GS pulses in Fig. 2). The velocity of the Bragg soliton increases with increasing amplitude (the delay $\Delta\tau$ — decreases). Experimental observations of Bragg solitons in MC based on a 10 micron thick YIG film with a groove depth of 1 µm and a period of 200 µm were also carried out.

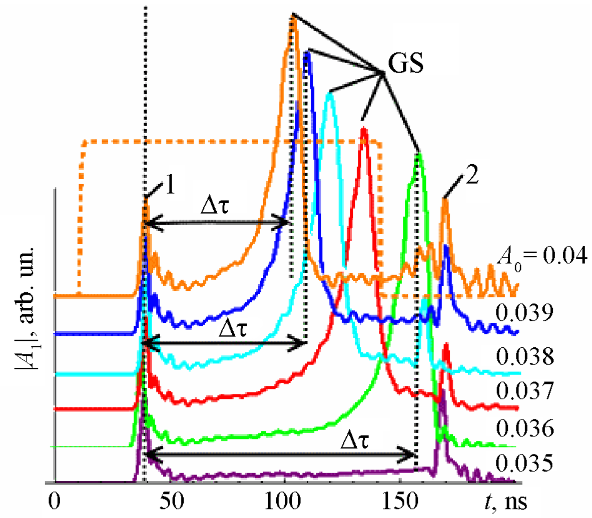


Fig. 2. Profiles of the input pulse (dotted curve) and the pulse at the MC output (solid curves) at different input pulse amplitudes (color online)

The features of the propagation of magnetostatic waves in MC with defects are considered. In particular, the MC with a periodic system of defects is considered — magnon superlattice (Fig. 3, *a*) [27]. By the method of crosslinking magnetic permeabilities described in [1], the dispersion relation for the MSSW in a superlattice with periodic boundary conditions in the form of a system of metal strips with two periods (l and L) is obtained. It is shown that in such a structure there is the formation of two band gaps at wave numbers and frequencies other than Bragg for MC with periods l and L (the shaded areas SL-3 and SL-4 in Fig. 3, *b*), and two gaps — at wave numbers and frequencies coinciding with Bragg (SL-1 and SL-2 in Fig. 3, *b*). The frequency interval and the interval of wave numbers between SL-3 and SL-4 is determined by the ratio of the periods l and L. Nonlinear effects in the propagation of spin waves in such a structure [28] are investigated.

A MC with periodic boundary conditions in the form of metal strips containing a distributed defect is considered (Fig. 3, *c*) [29]. The distributed defect was formed by breaking a ferromagnetic film with periodic boundary conditions and forming a film region with homogeneous boundary conditions. A wave model is constructed, an experimental study is carried out. It is shown that, depending on the width of the defect (D_l), the BG can be formed both higher in frequency and lower in frequency, relative to the BG of the MSSW in the MC without a defect.

3. Related Magnon Crystals

One of the key areas of research in the scientific group led by Yuri Pavlovich was the study of coupled magnonic crystals. Moreover, the object of the study was both lateral connected structures, ferromagnetic waveguides in which are in the same plane, and multilayer sandwich structures.

A theoretical model for describing the spin-wave evolution is constructed and dispersion relations for MSSW and MSDVW are obtained. The model is a system of four equations, the relationship between which is determined by two linear coupling coefficients: the first is — electrodynamic, due to the coupling between MSW propagating in different MC, and depending on the thickness of the dielectric (χ), the second is — determining the relationship between direct and reflected waves in one MC, which depends on the geometric dimensions of the periodic «cell» (κ).

On the basis of theoretical and experimental research, the mechanism of formation of band gaps is revealed. In Fig. 4, *a* the dispersion characteristics for the symmetric (dotted line 2) and antisymmetric (dotted line 3) normal waves in bound homogeneous films. The corresponding characteristics for reflected waves are indicated by $2'$ and $3'$. At the frequencies of phase synchronism, the interaction of the four described types of waves leads to the formation of BG (s, as, s/as, shown by fill). It is possible to form one, two, three or four BG in the region of the first Bragg resonance. In the insert to Fig. 4, *a* shows the dispersion characteristic for the MSSW in one MC. In this case, due to the interaction of a direct line (line 1) and reflected (line $1'$) waves form one BG (mc, shown by fill) [30]. The influence of the excitation method

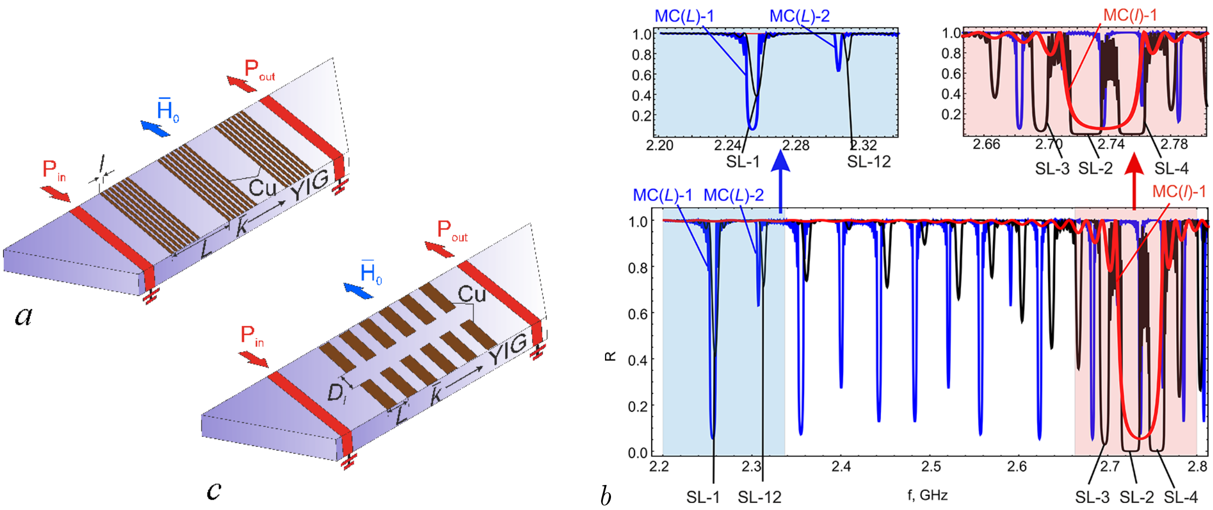


Fig. 3. Schemes of magnon superlattice (*a*) and MC with a line defect (*c*). *b* — Transfer characteristics of the MSSW in the MC with period l (red curves), MC with period L (blue curves) and in the magnon superlattice (black curves) (color online)

(excitation of one or two normal modes) on the formation of band gaps is considered. Thus, when only a symmetric normal wave is excited (signals of equal power in phase are fed to MC-1 and MC-2), one band gap is observed (the red curve in Fig. 4, *b*). When two normal waves are excited (the signal is fed to MC-1 or MC-2), two band gaps are observed — the band gap for symmetric waves and the band gap for antisymmetric waves (the blue curve in Fig. 4, *b*) [31].

The features of nonlinear processes in the propagation of MSSW in the layered structure of MC-1/MC-2 are considered (Fig. 5, *a*). A nonlinear wave model has been constructed to describe the spatial-wave evolution of the MSDVW and MSSW. The model is a system of four coupled wave equations describing the linear and nonlinear relationship between the amplitudes of the envelopes of direct and reflected waves in MC-1/MC-2. Based on the numerical solution of wave equations and experimental studies, such nonlinear effects as single and double nonlinear switching have been identified (Fig. 5, *b*, *c*, *d*), nonlinear pumping of Bragg solitons.

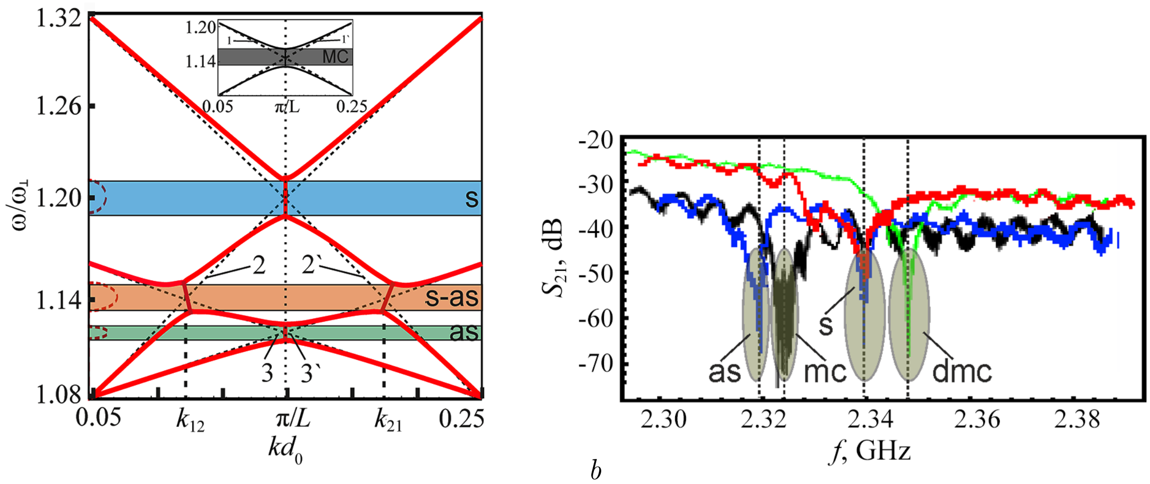


Fig. 4. *a* — Theoretical dispersion characteristics of MSSW in MC-1/MC-2 with period L. On the insert there are characteristics of the MSSW in a single MC. *b* — Experimental frequency response of MSSW in laterally coupled MC-1 and MC-2 with excitation of a symmetric wave (red curve) and with excitation of symmetric and antisymmetric waves (blue curve), as well as in a single MC (black curve) and a double-width MC (green curve). The band gaps are highlighted by ovals (color online)

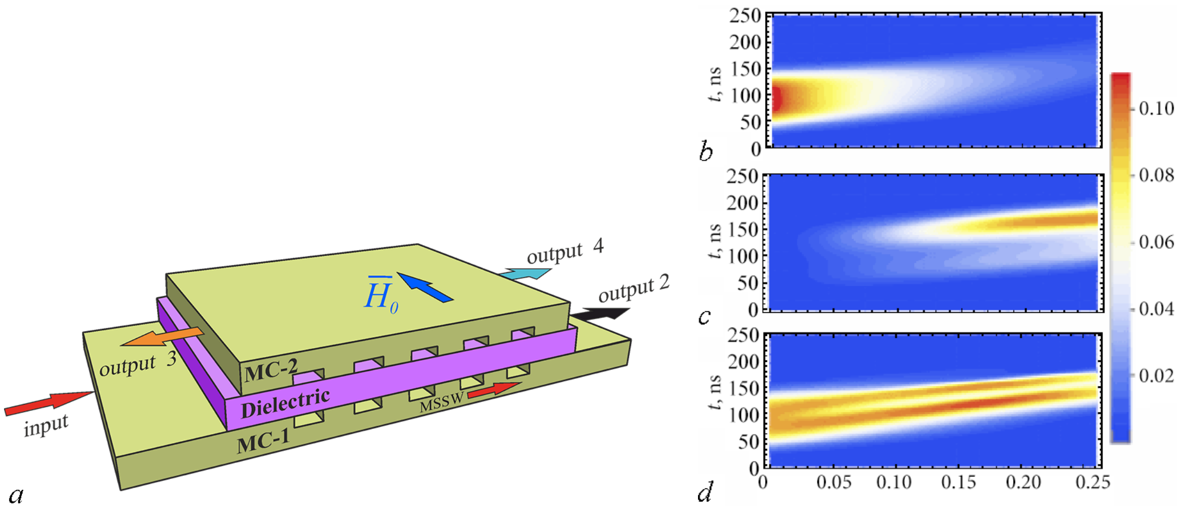


Fig. 5. *a* — Scheme of the MC-1/MC-2 structure. The spatiotemporal evolution of the amplitude of the envelope of the forward wave in MC-2 at the amplitude of the input signal $A_0 = 0.01$ (*b*) and $A_0 = 0.04$ (*c*); *d* — in MC-1 at $A_0 = 0.07$ (color online)

In particular, it is shown that in the MC-1/MC-2 structure, depending on the coupling coefficients describing the linear coupling between direct and reflected waves in MC-1 (MC-2) (parameter κ) and between direct (reflected) waves in neighboring layers (parameter χ), various signal separation modes are implemented for two or three ports of the coupled structure with an increase in input power (Fig. 6). A “single nonlinear switching” of type 1 is possible (the SS-1 parameter range in Fig. 6) — at low input power, the pulse is reflected from the MC-1, at high — it exits the MC-1; "single nonlinear switching"of type 2 (region SS-2 in Fig. 6) — at low input power, the pulse exits MC-2, at high — from MC-1. If the coupling coefficients are close in magnitude, the effect of “double nonlinear switching” is possible. With a “double nonlinear switching” of type 1 (the DS-1 region in Fig. 6) — at low input power, the pulse is reflected from the MC-2 (see Fig. 5, *b*), when the input power increases, the first switching takes place — the pulse passes through the coupled structure and exits MC-2 (see fig. 5, *c*), with a further increase in power, a second switching takes place — the pulse exits MC-1 (see Fig. 5, *d*). With "double nonlinear switching"of type 2 (the DS-2 parameter area in Fig. 6) — at low input power, the pulse is reflected from MC-1, with an increase in input power, the first switching takes place — the pulse is reflected from MC-1, with a further increase in amplitude, the second switching takes place — the pulse exits MC-2. The main mechanism of the double nonlinear switching effect is the simultaneous manifestation of nonlinear effects characteristic of a single MC and for two homogeneous films having different threshold capacities [32].

In the future, the development of Mandelstam-Brillouin spectroscopy technology made it possible to observe the effect of "double nonlinear switching"of the type 1 [33]. The effect of double nonlinear switching of type 1 allows us to consider the MC-1/MC2 structure as a basic element for multifunctional signal processing systems. The MC-1/MC2 structure is a four-port structure with one input and four outputs (see Fig. 5, *a*). When removing the signal from port 3, the structure performs the functions of a power limiter, when removing the signal from port 4, there is a separation of signals in a certain power range, when removing the signal from port 2 — suppression of weak signals. When removing the signal from all ports, the structure allows you to perform the functions of spatial separation of signals of different power levels: a low-power signal will come out from port 3, a high-power signal — from port 2, medium-power — from port 4.

4. Structures magnon crystal/semiconductor

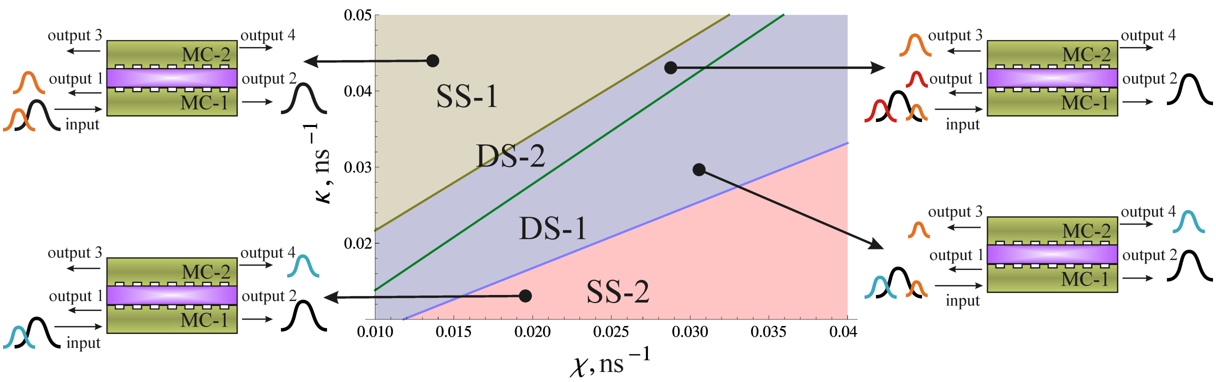


Fig. 6. A parameter map (κ, χ) illustrating various regimes of nonlinear switching with an increase in the amplitude of the input signal. On the inserts there are schemes of the MC-1/MC-2 structures (*zy* projection) (color online)

and magnon crystal/normal metal

An important direction that was laid down in the early works of Yuri Pavlovich is the study of the effect of various finite conductivity loads on waves propagating in ferromagnetic films [34, 35]. Such loads can be both metal and semiconductor screens. In this case, it is relevant to study the effect of the ordered movement of charges — electric current in a semiconductor and the ordered movement of spins — spin current in NM on the propagation of magnetostatic waves in the MC.

In particular, the influence of electric current on the propagation of MSSW in a MC loaded with a SC layer (MC/SC) is considered. By the method of crosslinking magnetic permeability at the boundaries of layers, first described in [1], a dispersion relation is obtained, a nonlinear wave model is constructed to describe the spatio-temporal evolution of the envelope in the structure under study. For the experimental study, a structure based on an MC loaded with a plate of doped silicon, through which an electric current was passed, was used. On the AFR of the MSSW in such a structure, in the absence of current, a pronounced minimum is visible, which corresponds to the band gap (the red curve in Fig. 7, *a*). If the movement of charges in the PP is co-directed with the propagation of the MSSW, which shifts to the low-frequency region. The opposite direction of movement of the charges in the SC does not affect the position of the [36] in any way.

Studies of nonlinear phenomena in MC/SC have been carried out. It is shown that with an increase in the input power, the formation of a Bragg soliton takes place (GS pulses in Fig. 7, *b*). The threshold of formation, velocity and amplitude of the soliton is determined by the velocity and direction of movement of charges in SC [37].

The effect of spin current on the character of spin-wave processes during the propagation of MSW in a MC loaded with a layer of normal metal (MC/NM) is considered. When an electric current flows in NM, due to the spin Hall effect, a spin current flows in a direction perpendicular to the electric current, associated with the movement of electrons with a given direction of spins. A wave model is constructed, and the dispersion relation for the MSSW in such a structure is obtained. The possibility of controlling the characteristics of the band gaps in the MC using a spin current in NM is considered. The effect of spin current on nonlinear effects during the propagation of magnetostatic waves in structures of the MC/NM type is considered and FF-1/NM/FF-2.

5. Structures magnon crystal/ferroelectric

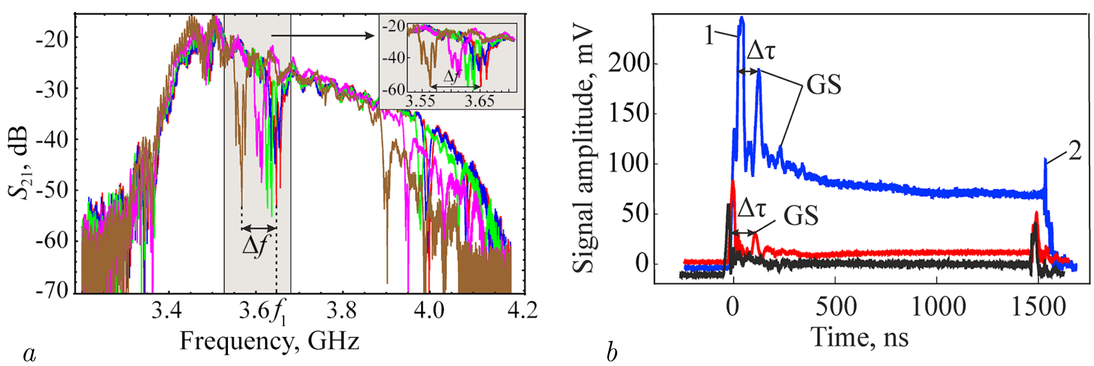


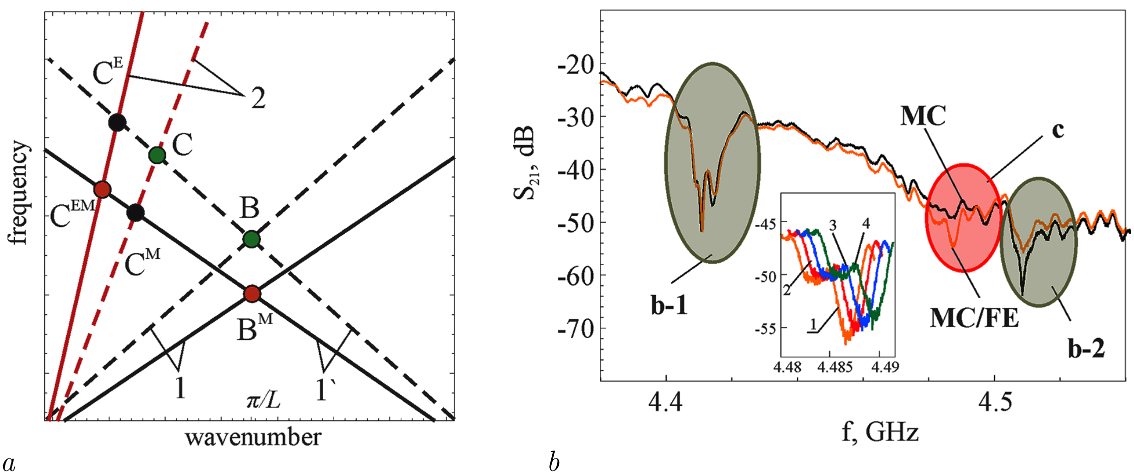
Fig. 7. *a* — MSSW frequency response in the structure MC/SC at an input power of 11 dBm and electric field strength: 0 (red curve), 2.5 kV/cm (blue curve), 5 kV/cm (green curve), 7.5 kV/cm (pink curve), 10 kV/cm (brown curve). *b* — Time profiles of output pulses at different input power and voltage levels: 11 dBm and 0 kV/cm (black curve), 23 dBm and 0 kV/cm (red curve), 30 dBm and 0.2 kV/cm (blue curve)

and magnon crystal/piezoelectric

Ferroelectric and piezoelectric loads are another type of loads capable of providing electrical control of the nature of spin-wave excitations in ferromagnetic films. In this case, it is relevant to study the influence of electromagnetic waves in the load FE and deformations in the load from the PE on the propagation of magnetostatic waves in the MC.

In the structure of MC/FE, due to the interaction of the MCW in the MC and the electromagnetic wave in the FE, a hybrid electromagnetic-spin wave is formed. A wave model is constructed and dispersion relations for HEMSW are obtained. The dispersion characteristic of the HEMSW has two branches corresponding to fast and slow waves. It is shown that the mechanism of formation of band gaps in such a structure is as follows. Due to the interaction of a direct line (straight line 1 in Fig. 8, *a*) and reflected (straight line $1'$ in Fig. 8, *a*) slow HEMSW at the frequency of phase synchronism (marked with a dot B), the main BG is formed (the mechanism of its formation is similar to the mechanism of BG formation in a single MC). Due to the interaction at the phase synchronism frequency (marked with a dot C) of the direct fast HEMSW (direct 2) and the reflected slow HEMSW (direct $1'$) forms a hybrid BG. In a single MC, such a gap is not formed.

Taking into account only the magnetic nonlinearity, an increase in the amplitude leads to a decrease in the magnetization of the MC. As a result, the center of the main band gap turns out to be lower in frequency (point B^M) than in the linear case shown by the dot. The center of the hybrid band gap (point C) shifts down in frequency and wave number and falls into the point C^M. Taking into account only electrical nonlinearity, with an increase in amplitude, the value of the dielectric constant of the FE decreases (which is typical for opaque dielectrics). In this case, the position of the center of the hybrid zone is shifted up in frequency (point C^E) and down in wave number, relative to the linear case. The position of the center of the main gap is not affected by electrical nonlinearity. Taking into account both types of nonlinearity, the center of the hybrid band gap will be located, respectively, at the point C^{EM}, and the center of the main zone — at the point B^M. It can be seen that the effect of electrical nonlinearity on the position of the hybrid band gap is opposite to the effect of magnetic nonlinearity and, in general, can compensate for it.



a *b*

Fig. 8. *a* — Schematic representation of the dispersion characteristics of forward (line 1) and reflected (line $1'$) slow GEMSW, as well as forward (line 2) and reflected fast GEMSW. The dotted lines show linear regimes, the solid ones — nonlinear ones. *b* — The frequency response of MSSW in MC (black curve) and GEMSW in the structure MC/FE (orange curve). In the insert, there is the fragment of the frequency response of the GEMSW in MC/FE at the electric field strength: 0 (curve 1), 6 kV/cm (curve 2), 12 kV/cm (curve 3), 16 kV/cm (curve 4). The band gaps areas are marked with ovals (color online)

The possibility of dual control (electric and magnetic fields) of the characteristics of the band gaps [38] is shown. On the experimental frequency response of a single MC (the black curve in Fig. 8, *b*) dips corresponding to the first (b–1) and second (b–2) main Bragg band gaps are visible. When a layer of FE (a plate of strontium barium titanate (BST)) is applied to the MC, an additional dip appears on the frequency response (orange curve) corresponding to the hybrid band gap (*c*). When an electric field is applied to the FE layer, the hybrid band gap shifts up in frequency, as shown in the box to Fig. 8, *b*.

The structure of the type MC-1/FE/MC-2 [39] is considered. The dispersion curve for HEMSW in this case is split into three branches corresponding to the fast and two slow HEMSW in. At the frequencies of phase synchronism, due to the interaction of three direct and three reflected waves, five band gaps are formed (if the structure is symmetrical). Three gaps are the main ones, since they are formed due to the interaction of slow HEMSW In and the mechanism of their formation is similar to the mechanism of the formation of BG in the structure of MC-1/MC-2. The two gaps are hybrid, as they are formed due to the interaction of fast and slow HEMSW and such gaps are not formed in the MC-1/MC-2 structure.

The principle of frequency multiplexing/demultiplexing of signals with magnetic and electric control based on the MC/FE/FF structure is proposed.

The effect of deformation on the propagation of magnetostatic waves in the MC is considered. In particular, the influence of magnetostriction of a ferromagnetic medium on the nature of spin-wave processes during the propagation of MSSW in the MC is considered. MSSW, due to magnetostriction, excites a transverse elastic wave in the MK. In turn, due to the interaction of the MCW and the elastic wave, a magnetoelastic wave is formed. A theoretical model is constructed and a mechanism for the formation of additional BG due to the interaction of direct and reflected magnetoelastic waves is revealed.

The effect of deformation on the character of spin-wave processes during the propagation of MSW in a MC loaded with a piezoelectric layer (MC/PE) is considered. When an electric field is applied to the PE layer, deformation occurs. The deformation is transmitted by the MC with magnetostriction, leads to a change in the internal effective magnetic field and affects the characteristics of the BG. Dispersion relations for MSSW in MC/PE are obtained. The possibility of dual control of the width and position of the BG with a change in the magnitude of the magnetic and electric fields [40] is demonstrated.

It is shown that if in the structure of MC/PE layer has hysteresis properties (for example, hafnium oxide), then on the basis of such a structure, it is possible to implement the functions of recording, storing and reading information.

Conclusion

The results presented in the review expand the fundamental understanding of physical processes in periodic magnetic structures. In particular, the wave model describing the propagation of magnetostatic waves in coupled magnon crystals opens up the possibility of studying a wide range of nonlinear phenomena caused by the influence of coupling and periodicity in layered periodic structures based on magnetic films. It may also be of interest in the study of nonlinear phenomena in coupled periodic structures of various physical nature.

At the same time, the presented results are of general scientific importance for understanding the basic laws of the joint influence of coupling, periodicity and interactions of different physical nature (the effect on the spin wave of deformation in periodic structures with PE, electromagnetic wave in structures with FE, electric current in structures with SC, spin current in structures with

NM).

In applied terms, the identified effects open up wide possibilities for creating new devices of spin-wave electronics in the microwave range with the possibility of dynamic control of characteristics when changing the electric and magnetic fields, as well as the power of the input signal. In particular, based on the structure of coupled magnon crystals, it is possible to create devices for spatial separation of signals of different power levels, suppression of high-power signals, suppression of weak signals, isolation of signals in a certain power range [41]. Based on the coupled magnon crystal and ferromagnetic film separated by a ferroelectric layer, it is possible to create a device that allows frequency multiplexing/demultiplexing of signals [42]. On the basis of an MC with a piezoelectric load having the property of hysteresis, a functional element can be created that records, stores and reads information [43].

In our opinion, the ideas of Yuri Pavlovich, laid down in the book «Magnetostatic waves in microwave electronics» and developed in the results given in this review, will inspire scientists for more than a decade and give food for the mind and creative search for the benefit of fundamental and applied world science!

The authors express their great gratitude and appreciation to the Dr.Phys.-Math.Sci.Professor Yu. P. Sharaevsky for a huge amount of knowledge, creative inspiration, invaluable discussions and breakthrough ideas that made it possible to obtain the presented results.

References

1. Vashkovskii AV, Stalmakhov VS, Sharaevskii YP. Magnetostatic Waves in Microwave Electronics. Saratov: Saratov University Publishing; 1993. 312 p. (in Russian).
2. Gurevich AG, Melkov GA. Magnetization Oscillations and Waves. Boca Raton: CRC Press; 1996. 464 p.
3. Barman A, Gubbiotti G, Ladak S, Adeyeye AO, Krawczyk M, Gräfe J, Adelmann C, Cotofana S, Naeemi A, Vasyuchka VI, Hillebrands B, Nikitov SA, Yu H, Grundler D, Sadovnikov AV, Grachev AA, Sheshukova SE, Duquesne JY, Marangolo M, Csaba G, Porod W, Demidov VE, Urazhdin S, Demokritov SO, Albisetti E, Petti D, Bertacco R, Schultheiss H, Kruglyak VV, Poimanov VD, Sahoo S, Sinha J, Yang H, Münzenberg M, Moriyama T, Mizukami S, Landeros P, Gallardo RA, Carlotti G, Kim JV, Stamps RL, Camley RE, Rana B, Otani Y, Yu W, Yu T, Bauer GEW, Back C, Uhrig GS, Dobrovolskiy OV, Budinska B, Qin H, van Dijken S, Chumak AV, Khitun A, Nikonov DE, Young IA, Zingsem BW, Winklhofer M. The 2021 magnons roadmap. J. Phys. Condens. Matter. 2021;33(41):413001. DOI: 10.1088/1361-648X/abec1a.
4. Nikitov SA, Kalyabin DV, Lisenkov IV, Slavin AN, Barabanenkov YN, Osokin SA, Sadovnikov AV, Beginin EN, Morozova MA, Sharaevsky YP, Filimonov YA, Khivintsev YV, Vysotsky SL, Sakharov VK, Pavlov ES. magnons: a new research area in spintronics and spin wave electronics. Phys. Usp. 2015;58(10):1002–1028.
DOI: 10.3367/UFNe.0185.201510m.1099.
5. Nikitov SA, Safin AR, Kalyabin DV, Sadovnikov AV, Beginin EN, Logunov MV, Morozova MA, Odintsov SA, Osokin SA, Sharaevskaya AY, Sharaevsky YP, Kirilyuk AI. Dielectric magnons: from gigahertz to terahertz. Phys. Usp. 2020;63(10):945–974. DOI: 10.3367/UFNe.2019.07.038609.
6. Gulyaev YV, Nikitov SA. magnon crystals and spin waves in periodic structures. Doklady Physics. 2001;46(10):687–689. DOI: 10.1134/1.1415579.
7. Chumak AV, Vasyuchka VI, Serga AA, Hillebrands B. Magnon spintronics. Nature Physics. 2015;11(6):453–461. DOI: 10.1038/nphys3347.
8. Krawczyk M, Grundler D. Review and prospects of magnon crystals and devices with

reprogrammable band structure. J. Phys. Condens. Matter. 2014;26(12):123202. DOI: 10.1088/0953-8984/26/12/123202.

9. Sharaevskii YP, Morozova MA, Grishin SV. Magnetostatic waves in microwave electronics. In: Trubetskov DI, Hramov AE, Koronovskii AA, editors. Methods of Nonlinear Dynamics and Chaos Theory in Problems of Microwave Electronics. Vol. 2. Nonstationary and Chaotic Processes. Ch. 11. Moscow: Fizmatlit; 2009. P. 348–379 (in Russian).
10. Chumak AV, Serga AA, Hillebrands B. magnon crystals for data processing. J. Phys. D. Appl. Phys. 2017;50(24):244001. DOI: 10.1088/1361-6463/aa6a65.
11. Ustinov AB, Drozdovskii AV, Kalinikos BA. Multifunctional nonlinear magnon devices for microwave signal processing. Appl. Phys. Lett. 2010;96(14):142513. DOI: 10.1063/1.3386540.
12. Sharaevsky YP, Sadovnikov AV, Beginin EN, Morozova MA, Sheshukova SE, Sharaevskaya AY, Grishin SV, Romanenko V, Nikitov SA. Coupled spin waves in magnon waveguides. In: Demokritov SO, editor. Spin Wave Confinement: Propagating Waves. 2nd ed. Ch. 2. New York: CRC Press; 2017. P. 47–76. DOI: 10.1201/9781315110820-3.
13. Khitun A, Bao M, Wang KL. magnon logic circuits. J. Phys. D. Appl. Phys. 2010;43(26):264005. DOI: 10.1088/0022-3727/43/26/264005.
14. Nikitin AA, Nikitin AA, Kondrashov AV, Ustinov AB, Kalinikos BA, Lähderanta E. Theory of dual-tunable thin-film multiferroic magnon crystal. J. Appl. Phys. 2017;122(15):153903. DOI: 10.1063/1.5000806.
15. Bukharaev AA, Zvezdin AK, Pyatakov AP, Fetisov YK. Straintronics: a new trend in micro- and nanoelectronics and material science. Phys. Usp. 2018;61(12):1175–1212. DOI: 10.3367/UFNe.2018.01.038279.
16. Gulyaev YV, Nikitov SA. Surface magnetostatic wave propagation in ferrite films with a periodic semiconductor structure. Soviet Physics, Solid State. 1983;25(8):2515–2517 (in Russian).
17. Sidorenko A. Functional Nanostructures and Metamaterials for Superconducting Spintronics: From Superconducting Qubits to Self-Organized Nanostructures. Cham: Springer; 2018. 270 p. DOI: 10.1007/978-3-319-90481-8.
18. Zhou Y, Jiao H, Chen YT, Bauer GEW, Xiao J. Current-induced spin-wave excitation in Pt/YIG bilayer. Phys. Rev. B. 2013;88(18):184403. DOI: 10.1103/PhysRevB.88.184403.
19. Wang Q, Pirro P, Verba R, Slavin A, Hillebrands B, Chumak AV. Reconfigurable nanoscale spin-wave directional coupler. Science Advances. 2018;4(1):e1701517. DOI: 10.1126/sciadv.1701517.
20. Morozova MA, Sharaevskii YP, Sheshukova SE, Zhamanova MK. Investigation of self-action effects of magnetostatic waves in ferromagnetic structures in terms of the system of Schrödinger equations with coherent or incoherent coupling. Physics of the Solid State. 2012;54(8):1575–1583. DOI: 10.1134/S1063783412080227.
21. Beginin EN, Morozova MA, Sharaevskii YP. Nonlinear effects of self-action of waves in 2D coupled ferromagnetic structures. Physics of the Solid State. 2010;52(1):79–86. DOI: 10.1134/S1063783410010130.
22. Sharaevskii YP, Malyugina MA, Yarovaya EV. Modulation instability of surface magnetostatic waves in ferromagnet-dielectric-ferromagnet structures. Tech. Phys. Lett. 2006;32(2):110–112.DOI: 10.1134/S1063785006020064.
23. Morozova MA, Romanenko DV, Matveev OV, Grishin SV, Sharaevskii YP, Nikitov SA. Suppression of periodic spatial power transfer in a layered structure based on ferromagnetic films. J. Magn. Magn. Mater. 2018;466:119–124. DOI: 10.1016/j.jmmm.2018.06.077.
24. Nikitov SA, Tailhades P, Tsai CS. Spin waves in periodic magnetic structures–magnon

crystals. J. Magn. Magn. Mater. 2001;236(3):320–330. DOI: 10.1016/S0304-8853(01)00470-X.
25. Bukesov SA, Stalmakhov VS, Sharaevskii YP. Surfase magnetostatic waves in a structure with periodic boundaries. In: Abstracts of III All-Union School — Seminar «Spin wave Microwave Electronics». Krasnodar; 1987. P. 31–32 (in Russian).
26. Morozova MA, Sharaevsky YP, Sheshukova SE. Mechanisms of formation of envelope solitons in periodic ferromagnetic structures. Izvestiya VUZ. Applied Nonlinear Dynamics. 2010;18(5):111–120 (in Russian). DOI: 10.18500/0869-6632-2010-18-5-111-120.
27. Morozova MA, Sadovnikov AV, Matveev OV, Sharaevskaya AY, Sharaevskii YP, Nikitov SA. Band structure formation in magnon Bragg gratings superlattice. J. Phys. D. Appl. Phys. 2020;53(39):395002. DOI: 10.1088/1361-6463/ab95c0.
28. Morozova MA, Matveev OV, Sharaevskii YP, Nikitov SA, Sadovnikov AV. Nonlinear signal processing with magnon superlattice with two periods. Appl. Phys. Lett. 2022;120(12):122407. DOI: 10.1063/5.0083133.
29. Morozova MA, Grishin SV, Sadovnikov AV, Romanenko DV, Sharaevskii YP, Nikitov SA. Band gap control in a line-defect magnon crystal waveguide. Appl. Phys. Lett. 2015;107(24):242402. DOI: 10.1063/1.4937440.
30. Morozova MA, Sharaevskaya AY, Sadovnikov AV, Grishin SV, Romanenko DV, Beginin EN, Sharaevskii YP, Nikitov SA. Band gap formation and control in coupled periodic ferromagnetic structures. J. Appl. Phys. 2016;120(22):223901. DOI: 10.1063/1.4971410.
31. Morozova MA, Grishin SV, Sadovnikov AV, Sharaevskii YP, Nikitov SA. magnon bandgap control in coupled magnon crystals. IEEE Trans. Magn. 2014;50(11):4007204.DOI: 10.1109/TMAG.2014.2321611.
32. Morozova MA, Matveev OV, Sharaevskii YP. Pulse propagation in a nonlinear system on the basis of coupled magnon crystals. Physics of the Solid State. 2016;58(10):1967–1974. DOI: 10.1134/S1063783416100243.
33. Morozova MA, Matveev OV, Romanenko DV, Trukhanov AV, Mednikov AM, Sharaevskii YP, Nikitov SA. Nonlinear spin wave switches in layered structure based on magnon crystals. J. Magn. Magn. Mater. 2020;508:166836. DOI: 10.1016/j.jmmm.2020.166836.
34. Prokushkin VN, Sharaevskii YP. Surface magnetostatic waves in a ferrite structure with impedance boundaries. Soviet Journal of Communications Technology and Electronics. 1987;32(8):1750–1752 (in Russian).
35. Prokushkin VN, Sharaevskii YP. Influence of reactive impedance load on magnetostatic waves characteristics. Journal of Communications Technology and Electronics. 1993;38(9):1551–1553 (in Russian).
36. Morozova MA, Romanenko DV, Serdobintsev AA, Matveev OV, Sharaevskii YP, Nikitov SA. Magnonic crystal-semiconductor heterostructure: Double electric and magnetic fields control of spin waves properties. J. Magn. Magn. Mater. 2020;514:167202. DOI: 10.1016/j.jmmm.2020.167202.
37. Matveev OV, Romanenko DV, Morozova MA. Linear and nonlinear effects in structures based on magnon crystals and semiconductors. JETP Letters. 2022;115(6):343–347. DOI: 10.1134/S0021364022100228.
38. Morozova MA, Grishin SV, Sadovnikov AV, Romanenko DV, Sharaevskii YP, Nikitov SA. Tunable bandgaps in layered structure magnon crystal–ferroelectric. IEEE Trans. Magn. 2015;51(11):2802504. DOI: 10.1109/TMAG.2015.2446763.
39. Morozova MA, Matveev OV, Sharaevskii YP, Nikitov SA. Tuning the bandgaps in a magnon crystal–ferroelectric–magnon crystal layered structure. Physics of the Solid State. 2016;58(2):273–279. DOI: 10.1134/S1063783416020207.
40. Grachev AA, Matveev OV, Mruczkiewicz M, Morozova MA, Beginin EN, Sheshukova SE,

Sadovnikov AV. Strain-mediated tunability of spin-wave spectra in the adjacent magnon crystal stripes with piezoelectric layer. Appl. Phys. Lett. 2021;118(26):262405. DOI: 10.1063/5.0051429.

41. Morozova MA, Matveev OV, Romanenko DV, Sharaevskii YP, Nikitov SA. Spin wave device for directional coupling of microwave signals of different power level. Patent No. 2702916 C1 Russian Federation, IPC H01P 1/22 : appl. 07.05.2019 : publ. 14.10.2019. Assignee: Kotel'nikov Institute of Radio Engineering and Electronics of RAS. 13 p. (in Russian).
42. Beginin EN, Sadovnikov AV, Popov PA, Sharaevskaya AY, Kalyabin DV, Stognii AI, Morozova MA, Nikitov SA. Functional component of magnons based on a multi-layered ferromagnetic structure. Patent No. 2702915 C1 Russian Federation, IPC H01P 1/218 : appl. 25.01.2019 : publ. 14.10.2019. Assignee: Kotel'nikov Institute of Radio Engineering and Electronics of RAS. 11 p. (in Russian).
43. Morozova MA, Matveev OV, Romanenko DV, Mednikov AM. Nanoscale multiferroics for magnon neuromorphic architecture. Nanoindustry. 2021;14(S7(107)):685–687 (in Russian). DOI: 10.22184/1993-8578.2021.14.7s.685.687.