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Experimental methods for the study of spin waves

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Abstract. *Purpose* of this paper is to give an overview of various experimental methods for investigation of spin waves characteristics. *Methods.* The paper presents a description of a number of experimental techniques, such as the probing method, the phase shift method, the method of measure of equiphase dependences, the method of intersecting wave beams, and the use of Fourier analysis of the complex transfer coefficient of spin waves to determine their spatial spectrum. The conditions for using the listed methods and the characteristics of spin waves that one can measure by means of these methods are discussed in detail. *Results.* The paper presents a number of fundamental results that have been obtained on the basis of described methods. For example, the probing method was successfully used to visualize the amplitude and phase distribution of spin waves in the ferrite film plane and, in particular, it was used to experimentally confirm the previously predicted appearance of super-directed propagation of surface and backward volume spin wave beams. The phase-shift measurement method made it possible to measure the dispersion dependence of spin waves in ferrite structures such as ferrite – metal and ferrite – dielectric – metal, where measurements cannot be made by the probing method. The method of measuring equiphase dependences of spin waves made it possible, in particular, to measure for the first time with great accuracy the value of an external magnetic field magnetizing an yttrium iron garnet film to saturation in various crystallographic directions. The method of intersecting wave beams has made it possible to clarify the mechanism of parametric instability of surface spin waves. Fourier analysis of the complex transfer coefficient of spin waves allowed to determine the spatial spectrum of these waves; in particular, dispersion dependences of higher modes of the backward volume spin wave were first measured using this method. *Conclusion.* The methods described in this paper may continue to be successfully used for investigations of spin waves characteristics in various magnon crystals, ferrite structures and meta-structures.

Keywords: spin wave, probing method, phase shift measurement, equiphase dependence, spatial Fourier analysis.

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Over the past ten years, studies of the characteristics of spin waves and their application in various fields of science and technology have gained a new powerful impetus for their development,

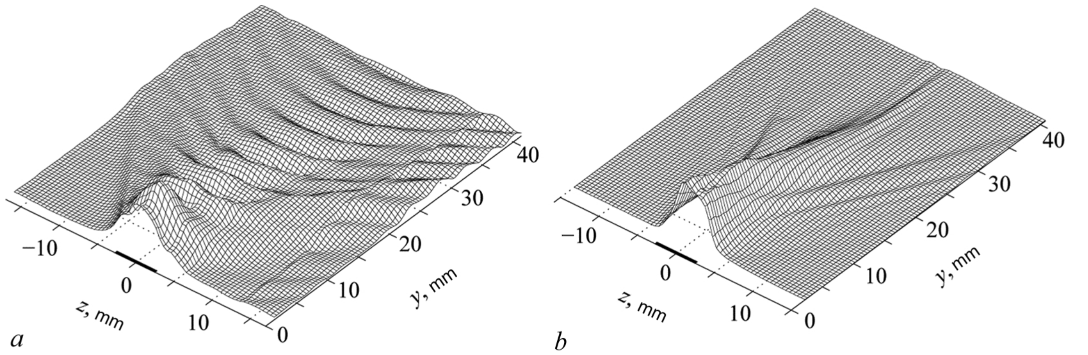

Fig. 1. Distribution of the amplitude of surface spin waves in the YIG – GGG – YIG structure at $kh < 1$ (a) and $kh \gg 1$ (b), where h is the YIG substrate thickness

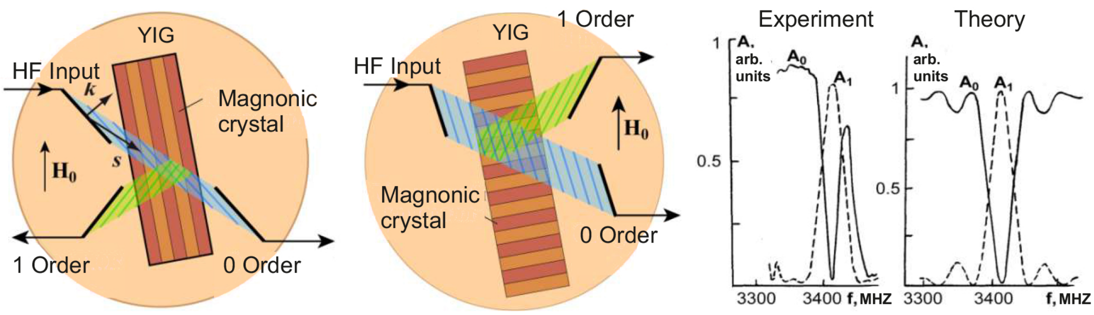

Fig. 2. Schematic of the experiment in the study of Bragg diffraction on a magnon crystal. Depending on the configuration, the diffracted beam can propagate both forward and backward. On the right is a view of the frequency response of the output signal in the vicinity of the Brillouin zone

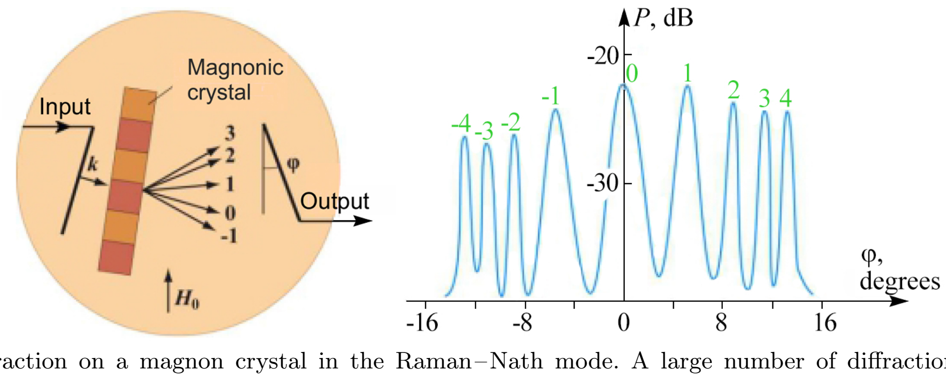

Fig. 3. Diffraction on a magnon crystal in the Raman–Nath mode. A large number of diffraction orders are observed

associated with the possibility of using these waves not only in magnonics and spintronics, but also in the creation of logic circuits in the development of computers, as well as in the development of nano-devices [1–6]. Now it is even difficult to imagine that the studies of spin waves at the end of the 20th century were practically suspended both in our country and abroad, and the main results of the studies that were carried out in the 30 years that have passed since the description of spin waves in the work [7] were presented in monographs [8–11], prepared by the remarkable scientists A. V. Vashkovsky, V. S. Stalmakhov, Yu. P. Sharaevsky, A. G. Gurevich, G. A. Melkov, V. V. Danilov, I. V. Zavislyak, M. G. Balinsky and B. A. Kalinikosom. These monographs have become the reference books for all spin wave researchers for many years.

Among the scientific collectives of Russia, which, after the collapse of the USSR, continued the research of spin waves and predetermined the current round of successful development of magnonics, there was a laboratory for the study of microwave properties of ferromagnets in the Fryazino branch of the Kotelnikov Institute of Radio Engineering and Electronics RAS. For 30 years since the beginning of the 1990s, a number of experimental and theoretical studies of the characteristics of spin waves in ferrite films and various structures based on them, including magnon crystals, as well as a number of studies of various physical effects using spin waves have been carried out in the laboratory. Below is a brief overview of the experimental methods developed in the laboratory to study the characteristics of spin waves after the publication of the monographs [8–11].

In the experimental study of spin waves, the basis for the creation of the vast majority of ferrite structures was relatively magnetized films of iron-trium garnet (YIG) on substrates of gallium-gadolinium garnet (GGG). The use of YIG films as part of ferrite structures provided effective excitation in the microwave range of spin waves with wave numbers of the order of $10...10^4$ cm $^{-1}$. The wave vector $\mathbf{k}$ and the group velocity vector $\mathbf{V}$ of spin waves are generally not collinear, and the wave can be the forward when the scalar product $(\mathbf{kV}) > 0$, and the backward when $(\mathbf{kV}) < 0$. A wave with a non-collinear orientation $\mathbf{k}$ and $\mathbf{V}$ can be briefly called a non-collinear wave.

The collectives of the Institute of Radio Engineering and Electronics of the USSR Academy of Sciences and Saratov State University were among the first in the world to conduct experimental and theoretical studies with non-collinear spin waves [12–15]. For this purpose, experimental setups were created in the laboratory for the study of microwave properties of ferromagnets of the IRE of the USSR Academy of Sciences. Exciting and receiving transducers of these setups could freely move along the surface of the ferrite film (structure) and rotate around the normal to the surface, which made it possible to excite and receive width-limited wave beams of spin waves with any relative orientation of the vectors $\mathbf{k}$ and $\mathbf{V}$. At first, identical exciting and receiving spin wave transducers were used in the experiments. When moving the receiving transducer along the group velocity vector, the dispersion dependences of spin waves in various ferrite structures were measured. However, it soon became clear that if a movable probe with a small aperture of 0.5 mm was used instead of an identical receiving transducer, a pattern of amplitude and phase distribution for spin wave could be obtained by the moving of this probe along the ferrite film (or structure) surface.if a movable probe with a small aperture of 0.5 mm was used instead of an identical receiving transducer, a pattern of amplitude and phase distribution for spin wave could be obtained by the moving of this probe along the ferrite film (or structure) surface. For this purpose, one of the experimental setups was equipped by probe displacement and rotation mechanisms with probe position sensors, and this method of measurement of spin waves characteristics was called the probing method. With the development of computer technology, both the method itself and the experimental setup were significantly

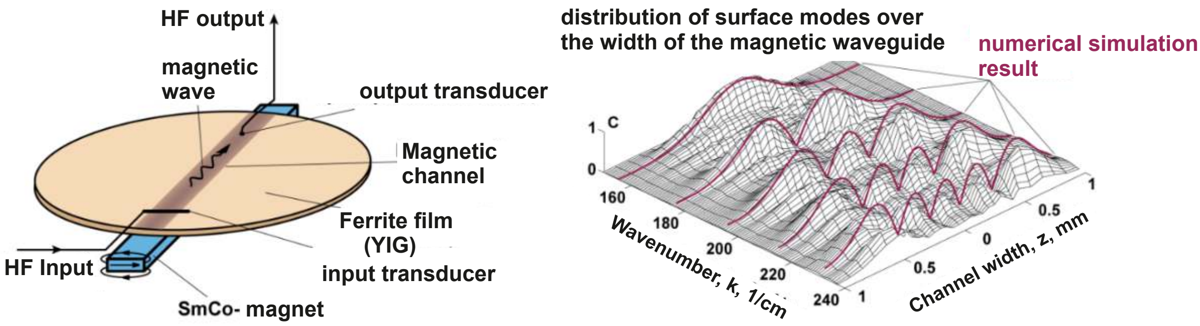

Fig. 4. Surface spin modes in a magnetic waveguide (experimental scheme and mode distribution)

improved. Computer processing of experimental data and subsequent Fourier analysis of the complex signal made it possible to solve a very important problem — to visualize the propagation of spin waves in the plane of the structure under study at a fixed frequency (Fig. 1) [16], that is, to observe the formation and propagation of a wave beam, the distribution of amplitude and its outlines wave fronts.

The probing method proved to be very effective in studying the diffraction of spin waves through a low-contrast magnon crystal (MK, MC), which is formed in a ferrite film due to the stationary spatially periodic modulation of the magnetic field applied to the film when a highly coercive magnetic waveform is located on its surface (Fig. 2, 3) [17, 18].

In addition, when various magnetic elements were placed under the film, different configurations of an inhomogeneous magnetic field were implemented in the film plane, that allow to control the trajectory and beam width of the spin wave. For example, waveguide propagation of spin waves was realised by placing extended miniature magnets near the film. This propagation was characterised by the presence of several modes and waveguide coupling between closely spaced waveguides (Fig. 4) [19].

In addition, the probing method has been successfully used to study the diffraction of spin waves on various inhomogeneities in order to visualise the resulting diffraction patterns. In particular, this method has recently been used to experimentally confirm the previously predicted [20, 21] appearance of superdirected propagation of surface and backward volume spin wave beams(Fig.5) [22, 23].

It turned out that the probing method could be further improved to obtain wave distribution patterns over a wide frequency range during a single pass of the probe along the surface of the structure.

For this purpose, simultaneously with slow movement of the probe along z axis of the structure surface a fast sawtooth frequency change of the vector analyser was carried out in a certain frequency interval $f_{\text{in}} << f < f_{\text{fin}}$, and the probe shift was very small during the period of sawtooth voltage. As a result of this improvement, it became possible to measure the distribution of the complex transmission coefficient $K(y, z, f)$ depending on the frequency f and the coordinates y, z along the surface of the structure. The subsequent Fourier analysis of the complex transmission coefficient $K(y, z, f)$ made it possible to actually automate the measurement of the dispersion dependencies of spin waves (Fig. 6) [24].

It should be noted that although the probing method has appeared to be very effective in investigating of spin waves characteristics, some experimental problems were impossible to perform using this method. For example, it is known that in practice it is impossible to measure the dispersion dependence of spin waves in ferrite structures such as ferrite – dielectric – metal using the probing method, since the small thickness of the dielectric gap (less than 1-2 mm) does not allow to move the probe under the metal screen and measure with it. Probing of the film through a substrate adjacent to another surface of the ferrite film is ineffective, since the GGG substrate has a thickness of 0.5 mm and a relative permittivity of $\varepsilon = 9$. Therefore, to determine the dispersion relation in such ferrite structures a method was developed based on measurement of phase shifts occurring when the thickness of the air gap is smoothly increased to about 10 mm (at such a gap the spin waves in the YIG film do not sense the metal screen) and subsequent comparison of the phase-frequency characteristics in the initial structure and in the final one with the known dispersion (in this case — in a free film).

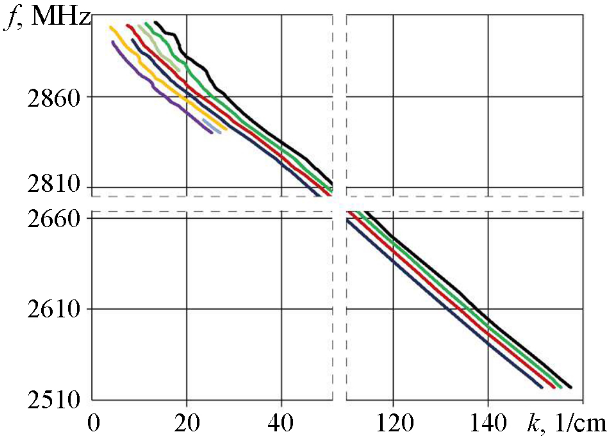

Fig. 6. Dispersion dependences of $f(k)$ satellite modes, into which the first mode of backward volume spin wave (BVSW) in a highly homogeneous magnetic field splits due to the existence of several layers with close magnetic parameters in the ferrite film (color online)

When measuring these phase shifts, it is necessary to take into account the sign of the phase difference. Depending on this sign, the dispersion dependence of the initial structure under study will be shifted relative to the dispersion dependence in the free film either towards higher values of the wavenumber or towards lower values of the wavenumber. If we use the terminology of optics, we can say that the initial structure can be either more or less dense in optical terms compared to the final structure. The description of this method, which can be conditionally called the method of measuring phase shifts, as well as the features and conditions of its use are described in more detail in the work [25].

To implement the method described

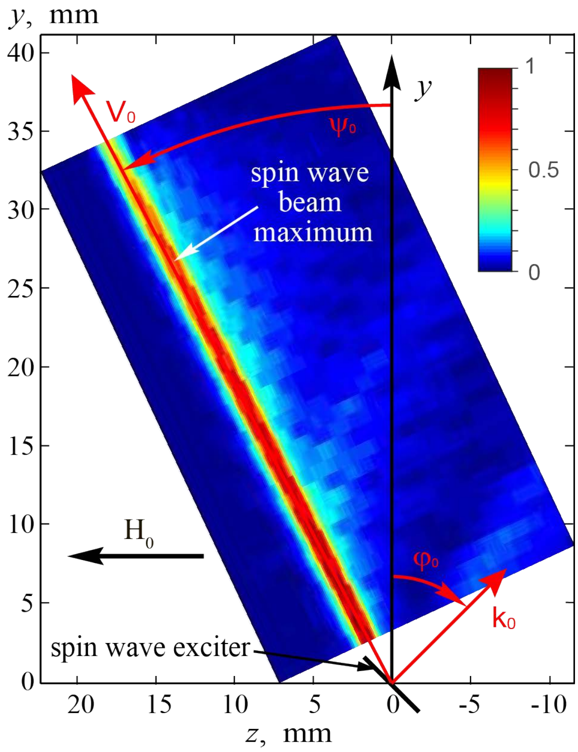

Fig. 5. Experimental amplitude distribution of the superdirected surface spin wave beam in the ferrite film plane for the following beam parameters: $f_0 = 2999$ MHz, $k_0 = 56.5$ cm^{-1}, $\lambda_0 = 1110$ μm, $\lambda_0/D = 0.222$, $\varphi_0 = -45°$. The color change (or gray shade) corresponds to a 3 dB change in the spin wave amplitude relative to the maximum amplitude. The absolute angular width of the beam at 0.5 was $\Delta\psi = 0.4°$ (color online)

above, another experimental setup was created, specially adapted to study the characteristics of spin waves in such structures in which it is impossible to use the probing method. Using the method of phase shifts measurement, the dispersion dependences of spin waves were measured in such structures as ferrite–metal (F–M, F–M), ferrite–dielectric–metal (F–D–M, F–D–M),

ferrite – high-temperature superconductor (F–VSP, F–HTSC) and ferrite – lattice of metal strips (F–RMP, F–MBL) [25–30] (see Fig. 7).

In particular, measurements of the dispersion relation for the first and last structures listed above have shown that the description of the surface spin wave (SSW) in the magnetostatic approximation leads to an incorrect distribution of the wave over the ferrite film. It is found that SSW magnetostatic potential described in magnetostatic approximation has a maximum on the metalized film surface, while in reality this is incorrect: the SSW has a tangent to the film plane (and hence to the metal plane) component of the microwave electric field, which should be zero on the metal. Therefore, in reality, the SSW energy in the F-M structure is localized at the opposite (non-metallized) surface of the ferrite film, which was confirmed by theoretical calculations [29, 30].

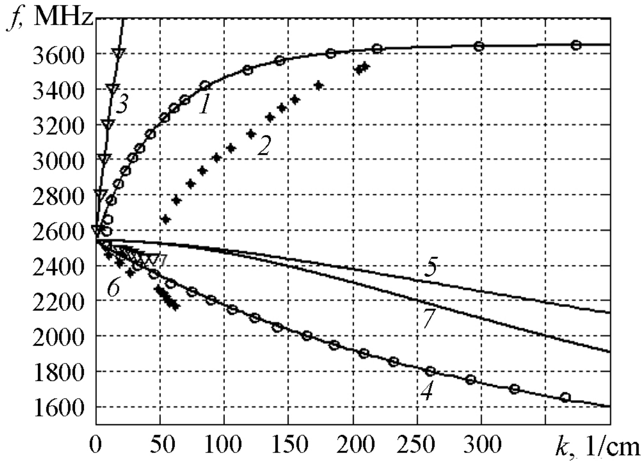

Fig. 7. Dispersion dependences $f(k_y)$. *1* — for SSW in the free film of YIG; *2* — for SSW in the F–MBL structure (experiment); *3* — for SSW in the F–M structure; *4* — for the first mode of BVSW in the free film of YIG; *6* — for BVSW in the F–MBL structure; *7* — for BVSW in the F–M structure (curves *1*, *3*, *4*, and *7* are experiments and calculations; curves *2* and *6* are experimental points connected by smooth curves; curve *5* is calculations). The calculation and the experiment were performed for the YIG film with thickness $d = 82$ μm, $4\pi M_0 = 1870$ G and external field $H_0 = 367$ Oe

In addition, tracking the phase change of the spin wave proved to be very effective in studying the characteristics of spin waves in films with a domain structure (DS). For example, the change of the initial frequency of the spin wave spectrum that occurs with a change of the external magnetic field H_0 can be measured by tracking the frequency change of the constant phase value corresponding to the wave numbers $k \sim 0$. Similarly, by changing the magnetic field H_0 (and keeping the distance between the transducers fixed), it is possible to monitor the frequency change of any other constant phase value corresponding to another constant value k and obtain "equiphase"dependencies $f_k(H_0)$. If then all the wave numbers are measured for some fixed value of the external magnetic field, then using the equiphase dependences $f_k(H_0)$, it is possible to construct the dispersion dependences of the spin wave in a film with DS immediately for any fixed value of the field H_0 (lying within the measuring range of the equiphase dependencies). Using this method, the equiphase and dispersion characteristics of spin waves in films with DS were measured (Fig. 8).

In addition, it was found that ferrite films of pure YIG can be conditionally divided into two types, differing in the unsaturated state both by the parameters, behavior and phase transitions of DS, and the characteristics of spin waves propagating in the films. Films of the first type have a high-contrast DS, and films of the second type have a low-contrast [31], and in films of the second type, the parameters of the DS and wave characteristics change hysteretically with a cyclic change in the magnitude of the applied field H_0 from about 0 to the saturating value

H_{sat} [32, 33], and in films of the first type, hysteresis changes in wave characteristics and DS parameters are not observed [34, 35].

As it turns out, it may be necessary to excite two wave beams simultaneously in a ferrite film in order to solve some fundamental questions. Thus, with the help of intersecting non-collinear wave beams of the SSW, the mechanism of the occurrence of its parametric instability was clarified. For a long time it was unclear whether nonlinear processes begin when the SSW is excited directly in the area of the exciting transducer (and therefore the electromagnetic field concentrated near the transducer acts as a pump), or parametric instability occurs already in the SSW itself after its excitation due to very much wave power. To answer this question unambiguously, it was necessary to separate the processes of SSW excitation and its parametric decay in time and space. This can be done by exciting the SSW in a ferrite film in a deliberately linear mode, and then somehow increase the energy density of the wave. If the first of the mechanisms described above is implemented in practice, the decay processes will not occur at all; if the second mechanism is implemented, then under certain conditions it will be possible to observe the occurrence of threshold phenomena in the experiment, starting from a certain section of the wave beam in which the energy density of the SSW exceeds the threshold value; moreover, in the sections lying closer to the exciting transducer, there will be no threshold phenomena. To answer this question, the following experiment was performed: two non-collinear wave beams were excited in a ferrite film so that their trajectories intersected, and so that the transducers exciting the beams received power slightly less than the threshold. The length of the trajectories of the wave beams was chosen so that both beams, having reached the intersection point, would have spent less than half of their power on dissipation (otherwise it would not have been possible to implement a nonlinear mode at the intersection point of the beams). The occurrence of a nonlinear regime at the intersection point of the wave beams (and its absence in the sections of the beam trajectories located up to the intersection point), observed in this experiment [36], confirmed that the second of the listed mechanisms of the occurrence of parametric instability of the SSW is implemented in practice.

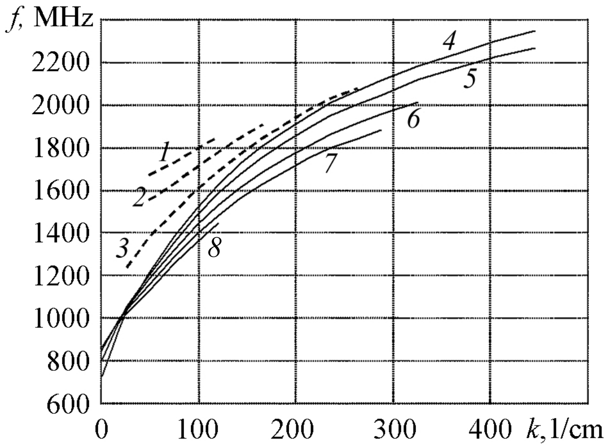

Fig. 8. Hysteresis change of the dispersion dependences $f(k)$ of the SSW when the YIG film is magnetized along one of the projections of the axes [111] on the film plane. The dashed curves were obtained when the H_0 field increased from ~ 0 to the saturating H_{sat} value, and the solid curves were obtained when the H_0 field decreased from the saturating H_{sat} value to ~ 0. The curves were measured at the following $_0$ magnetic field values (Oe): 4.7 (*1* and *7*); 11 (*2* and *6*), 21.7 (*3* and *5*); $H_0 = H_{sat} = 33.5$ (*4*); 2.5 (*8*)

Note that at present experiments to measure the characteristics of spin waves are often carried out by the Brillouin light scattering (BLS) method on them [37, 38], which, although it has a higher resolution in comparison to the probing method, is inferior to the latter by 1 - 2 orders of magnitude in the area of the film surface on which measurements can be performed. At the same time, the methods described above, such as spatial Fourier analysis and the method of measuring phase shifts, can also be used together with the Brillouin light scattering method for experimental measurement of the characteristics of spin waves.

Thus, there are considered in this paper the experimental methods of investigation of spin characteristics such as probing method, method of phase shift measurements, method of measuring equiphase dependences and using Fourier analysis of the complex transfer coefficient to determine the spatial spectrum of spin waves. The conditions for using these methods are discussed, as well as the results obtained using these methods.

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