Superdirectional beam of surface spin wave

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Abstract – The visualized diffraction patterns of a surface spin wave excited by an arbitrarily oriented linear transducer are investigated experimentally in the plane of a tangentially magnetized ferrite film for the case in which the transducer length $D$ is much larger than the wavelength $\lambda_0$. It is shown experimentally and theoretically that the angular width of a diffracted surface spin wave beam in an anisotropic ferrite film can take values greater or less than $\lambda_0/D$ and can also be zero. For the last case a superdirectional (non-expanding) beam of the surface spin wave is observed experimentally: the smearing of the beam energy along the film plane is absent and the length of the beam trajectory is maximal ($\sim 50$ mm). It is found that the well-known Rayleigh criterion used in isotropic media cannot be used to estimate the angular width of spin wave beams. The experimental results are in good agreement with theoretical investigations, predictions, calculations and formulas obtained recently.

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Introduction. – The development of magnonics during the last decade has led both to the design of functional magnonic devices and to the discovery of new theoretical fundamental laws for magnetic waves (see, for example, monographs [1–3] including references therein and the latest references [4–19]). In particular, recently it was investigated theoretically two-dimensional diffraction patterns arising in the far-field region of a ferrite film surface for the common geometry, when a plane surface spin wave with non-collinear group and phase velocities is incident on the wide slit in an opaque screen with arbitrary orientation [8,19]. In contrast to a similar problem for isotropic media it was found in magnetostatic approximation that the angular width $\Delta\psi$ of the diffracted spin wave beam is defined not only by the ratio $\lambda/D$ (here $\lambda$ is the incident wavelength, and $D$ is the slit length) but also by the mathematical properties of isofrequency dependence (ID) for the diffracted wave. In other words, ID can be termed as “section of wave vector surface”, “section of the isoenergy surface”, “equifrequency line”, etc. (the concept of ID is discussed in detail in sect. 4 of ref. [5]). The general formula for the angular width $\Delta\psi$ of a diffracted beam was derived for the case $\lambda/D \ll 1$ as a result of this investigation. It was shown that this formula is valid not only for various types of spin waves, but also for other waves, propagating in various anisotropic media and structures (including metamaterials, which are characterized by ID too). As follows from the obtained formula, in contrast with the Rayleigh criterion the angular width of the beam in anisotropic media can not only take values greater or less than $\lambda_0/D$, but also be equal to zero under certain conditions [8]. It should be noted that the theory in ref. [8] is also valid for the case in which a spin wave beam is excited by an arbitrary oriented linear transducer with length $D$ (this assumption is justified in sect. 9 of [8]). Thus, analysing the mathematical properties of the wave ID in various anisotropic media and structures, one can find out specific geometries in which the beams with zero angular width (or superdirectional beams) are excited.

The formation of narrow directional spin wave beams is an important problem of magnonics. The attempts to solve this problem were made in early studies of dipole spin waves, which are also called magnetostatic waves [20]. For example, the lens [21] and the excitation transducer [22] of a special shape were designed to focus the spin wave beam at a given point. In addition, it was found that if the surface spin wave is excited by the small transducer (with a length $D$ of the order of a spin wavelength $\lambda$), then
the energy of the excited beam is localized near the directions determined by the cutoff angles of the wave group velocity [23,24]. Twenty years later it was predicted in [25] that the energy of volume backward spin waves can be localized along certain directions corresponding to the normals to those points on the wave ID, in which the ID curvature is zero (in [25] for these propagation directions the terms “focusing” and “caustic propagation” were used). Recently, “caustic propagation” of spin waves, predicted in [25], was attempted in [6,10]. However, since in ref. [6] a spin wave exciter was used having size \( D \) of the order of the wavelength \( \lambda \) [6] or having size \( D < \lambda \) [10] (in [10] the diffraction of spin waves on the single antidote of diameter \( D \) is studied), the spin waves packet with a wide set of wave numbers was excited experimentally. In the best case the energy of the observed waves propagated at a distance of \( \sim 10 \) mm from the exciter [6]. Although the angular width of the observed wave packets was not measured, these packets were called both “non-diffracting” [6] and “caustic” [6,10] (although these terms are not equivalent). In addition, since initial spin waves in [6] were excited by a microstrip antenna in a narrow waveguide (and then the open end of waveguide excited waves in two-dimensional ferrite film area), it is obvious that the different waveguide modes excited experimentally influenced the resulting losses and diffraction patterns, too. Thus, both experiments [6,10] and experiments [22,23] were performed for cases in which the ratio between exciter size and spin wave length \( D \sim \lambda \) or \( D < \lambda \) was used, and in which, therefore, it is impossible to realize a non-diffracting wave beam.

In this paper, we present experimental investigations based not on the wave caustics study in the framework of geometric optics [25], but on the theoretical solution of the general diffraction problem for spin waves [8]. In accordance with [8], the angular width of the spin wave beam is varied and is determined by the wave vector, if the other parameters (frequency, external magnetic field, ferrite magnetization and film thickness) are fixed. Thus, in contrast to [6,10], it would be necessary for us to excite space-limited spin wave beams with a certain fixed wave vector (or with a very narrow spectrum of wave vectors near a certain value) and to measure the angular width of these wave beams. To realize this idea, we used a thin linear transducer whose length \( D \) was much longer than the spin wavelength \( \lambda \).

Below we demonstrate the validity of the general formula obtained in [8] and discuss experimental diffraction patterns of the surface spin wave beams propagated in a tangentially magnetized ferrite film for certain geometries, including the case in which the angular beam width can be equal to zero.

Experimental methods and setup. – The general scheme of the experimental setup is shown in fig. 1. The propagation of spin wave beams is studied in a yttrium iron garnet (YIG) film grown on a 0.5 mm thick substrate of gadolinium gallium garnet (GGG). A YIG film (5 in fig. 1) having diameter 76 mm, thickness \( s = 14.7 \mu m \) and magnetization \( 4\pi M_0 = 1855.8 \) Gs is magnetized to saturation by the tangential uniform magnetic field \( H_0 \) with a value \( H_0 = 471.5 \) Oe.

A microwave signal, propagating as a spin wave in the YIG film from input transducer 6 to output transducer 4, is generated and received by the vector network analyzer 1 and then the received data is processed and analysed by computer 2. The input transducer 6, exciting spin wave beam, and output receiving transducer 4 are made of a gold-plated tungsten wire 12 \( \mu \)m thick. The exciting transducer 6 has the length \( D = 5 \) mm and the receiving transducer 4 has the aperture \( L \sim 0.5 \) mm. Two identical systems provide in-plane displacement of the receiving transducer in two orthogonally directions of the YIG film plane (along the \( y \) and \( z \) axes). The receiving transducer 4 had also special position sensors 3 sending \( y \)- and \( z \)-transducer’s coordinates to computer 2. Thus, the receiving transducer 4 turns into a movable scanning probe. The exciting transducer, like the receiving transducer, was equipped by two systems: a system that moves it along the directions of Cartesian coordinates and a system that rotates it along the axis passing through the center of the exciting transducer perpendicularly to the ferrite film plane (these systems are not depicted in fig. 1). Thus, the position and orientation of the exciting transducer could be arbitrary and could be fixed on the film surface.

Since the spin wave energy distribution may occupy a large area compared with a YIG film surface of 76 mm in diameter, it is more effective to use the probe scanning method [26,27] for the study of spin wave beam distribution in the YIG film plane. Recently this method was improved cardinally [9] and now it is possible to visualise the distribution of the amplitude and phase of the spin wave.
along the film surface by means of computer signal processing (the probe scanning method and the experimental setup are described in detail in [9]).

**Theoretical calculations.** – For the case in which the spin wave beam is excited by an arbitrary oriented linear transducer, one can assume that the spin wave vector \( \mathbf{k}_0 \) is approximately perpendicular to the transducer line (this assumption is justified in sect. 9 of [8]) and, therefore, the general formula (30) in [8], describing the angular beam width \( \Delta \psi \), is simplified to the next form:

\[
\Delta \psi = \frac{\lambda_0}{D} \left| \frac{d\psi}{d\varphi}(\varphi_0) \right| .
\]

(1)

Here the angle \( \varphi_0 \) is the orientation of the wave vector \( \mathbf{k}_0 \) with respect to the \( y \)-axis (or the angle \( \varphi_0 \) may be considered approximately as the orientation of the transducer line with respect to the vector \( \mathbf{H}_0 \)); angles \( \varphi \) and \( \psi \) are orientations for an arbitrary wave vector \( \mathbf{k} \) and a corresponding group velocity vector \( \mathbf{V} \), respectively; \( d\psi/d\varphi(\varphi_0) \) is the derivative value, corresponding to the point of ID in which the wave vector \( \mathbf{k}_0 \) is ended (for more details see sect. 8 in [8]).

Characterizing spin wave beam parameters it is convenient to use both **absolute** angular beam width \( \Delta \psi \) and **relative** angular beam width \( \sigma \) which is equal to the ratio between the value \( \Delta \psi \) (in radians) and the value \( \Delta \psi_{\text{isotr}} = \lambda_0/D \) representing the angular width of a similar diffracted beam in isotropic medium (in radians too):

\[
\sigma = \frac{\Delta \psi}{\Delta \psi_{\text{isotr}}} = \frac{\Delta \psi}{\lambda_0/D} = \left| \frac{d\psi}{d\varphi}(\varphi_0) \right| .
\]

(2)

The relative angular width \( \sigma \) is a dimensionless quantity. From the physical standpoint, the value \( \sigma \) shows how much the value \( \Delta \psi \) is smaller (or greater) than the absolute angular width \( \Delta \psi_{\text{isotr}} \) for a similar beam (i.e., for the beam with the same ratio \( \lambda_0/D \)) propagating in isotropic medium.

Formula (1) shows that the angular beam width \( \Delta \psi \) is determined not only by the ratio \( \lambda_0/D \), but also by the derivative value \( d\psi/d\varphi(\varphi_0) \) characterizing the curvature of ID. So if one can find the structure (medium) and geometry (excitation topology), at which \( d\psi/d\varphi(\varphi_0) = 0 \), then one can observe a superdirectional (non-expanding) beam with angular width \( \Delta \psi = 0 \), i.e., the beam retaining a constant absolute width during its propagation!

As found in [8], the condition \( d\psi/d\varphi(\varphi_0) = 0 \) occurs for surface spin waves at frequencies lying not far from the initial frequency of the spectrum (for more details see fig. 7b, curve 2 in [8]):

\[
f_{\text{beg}} = \gamma \sqrt{H_0 (H_0 + 4\pi M_0)} .
\]

(3)

So, to observe a superdirectional (non-expanding) beam corresponding to the case \( d\psi/d\varphi(\varphi_0) = 0 \) we have calculated ID for the surface spin waves with various frequencies (fig. 2) and the corresponding dependences \( \psi(\varphi) \) (fig. 3(a)), \( d\psi/d\varphi(\varphi) \) and \( \sigma(\varphi) \) (fig. 3(b)) for the parameters of the YIG film mentioned above.
Fig. 4: (Colour online) Amplitude distribution of superdirectional spin wave beam in the plane of a ferrite film for the next beam parameters: \( f_0 = 2999 \text{ MHz} \), \( k_0 = 56.5 \text{ cm}^{-1} \), \( \lambda_0 = 1110 \mu\text{m} \), \( \lambda_0/D = 0.222 \), \( \varphi_0 = -45^\circ \), \( \Delta \psi_{\exp} = 0.4^\circ \), \( \sigma_{\exp} = 0.03 \). Colour or greyscale change corresponds to the 3 dB change of the spin wave amplitude relative to the maximal amplitude.

Since it is shown in [8] that numerical calculations of the value \( \sigma \) and calculations based on formula (2) coincide with good accuracy (see figs. 8–11 in [8]), only values of \( \sigma \) calculated by the formula (2) are given in fig. 3(b).

**Experimental results.** – Then to observe experimentally superdirectional beam propagation, we fixed the position of the exciting transducer at an orientation \( \varphi_0 = -45^\circ \) for which the relative angular width \( \sigma \) can be zero for frequency about 3 GHz (see fig. 3(b), curve 2). Since calculations based on the theory [8] do not take into account a number of parameters (such as anisotropy, applied field and magnetization inhomogeneity, etc.) influencing the spin waves characteristics, visualized patterns in the 120 MHz frequency band with a 1 MHz step are obtained for spin wave beams propagation at this orientation \( \varphi_0 \).

Below in fig. 4 we present the measured visualized pattern having the minimal angular beam width for the spin wave frequency \( f_0 = 2999 \text{ MHz} \). For the selected values \( f_0 \) and \( \varphi_0 \) the spin wave vector \( k_0 \) had magnitude \( k_0 = 56.5 \text{ cm}^{-1} \) (wavelength \( \lambda_0 = 1110 \mu\text{m} \)) and the ratio \( \lambda_0/D \) was 0.222.

The pattern in fig. 4 describes the distribution of the spin wave amplitude in the YIG film plane. The surface spin wave in fig. 4 has noncollinear orientation of the wave vector \( k_0 \) and group velocity vector \( V_0 \). It should be noted that in isotropic media such beam (having ratio \( \lambda_0/D = 0.222 \)) would have angular width about 12\textdegree, whereas in fig. 4 the spin wave beam has absolute angular width \( \Delta \psi_{\exp} = 0.4^\circ \) and relative angular width \( \sigma_{\exp} = 0.03 \). The propagation of a superdirectional spin wave beam can be compared with the collimation created by Nature.

Figure 5 shows how the angular width \( \Delta \psi \) of the spin wave beam varies with the change of wave frequency for the fixed orientation of an exciting transducer \( \varphi_0 = -45^\circ \). Calculated and measured dependences \( \Delta \psi(f_0) \) in fig. 5 are in good agreement. Note that since the exciting transducer length \( D \) is constant (5 mm), then the ratio \( \lambda_0/D \) is not a constant value in fig. 5. Since the frequency range of the surface spin wave spectrum can be varied by the change of the values \( H_0 \) and \( 4\pi M_s \) (see formula (3)), it is possible to realize the superdirectional propagation of the spin wave beam at other frequencies. Moreover, since the angular beam width \( \Delta \psi \) varies with the wave frequency (fig. 5), then the value \( \Delta \psi \) of the spin wave beam with fixed frequency can be varied also by the change of the bias field \( H_0 \).

Below we explain how the angular beam width \( \Delta \psi_{\exp} \) was measured. First of all, during the analysis of the visualized diffraction pattern, the line corresponding to the maximum beam amplitude was drawn (fig. 4). This line was approximated by a straight line, which can be considered as parallel to the group velocity vector \( V_0 \). Then for every maximum point of the beam we found coordinates of two points (lying along the perpendicular to the vector \( V_0 \)), in which the beam amplitude equaled half of maximum value. Connecting these points on the diagram, we obtained two lines lying on both sides of the maximum line and corresponding to the half-maximum level. These half-maximum lines were also approximated by straight lines in such way that both points of the near-field region (lying closer than 10 mm from the transducer center) and points of the farthest region (where the signal was very
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The angle between these straight lines was considered as an experimental angular beam width $\Delta \psi_{exp}$.

Near the 3000 MHz frequency the experimental value $\Delta \psi_{exp}$ in fig. 5 slightly differs from the calculated value $\Delta \psi_{th} \approx 0$. Here is the explanation: since the aperture of the receiving probe is 0.5 mm and the maximal length of the spin wave trajectory is $\sim 50$ mm (because of the presence of dissipation in real YIG films), the minimal angle that can be measured is $\sim \frac{0.5}{50/2} = 0.005$ rad $\approx 0.3^\circ$. So, it is possible to measure only the angular beam width exceeding $0.3^\circ$ by means of a probe with 0.5 mm aperture.

Mention must be made that the use of the probe with a smaller aperture does not increase the accuracy of measurement at the large distances because the probe sensitivity is decreased proportionally to the aperture size. We also note that, since the superdirectional beam does not expand practically, the orientation $\psi_0$ of the group velocity vector for this beam can be measured with the highest accuracy.

Since a superdirectional spin wave beam propagating over long distances without spreading can be used for the design of new spin wave devices, we give below its certain geometrical details, see refs. [24,28] and sect. 6.3 in ref. [5].

In order to demonstrate how strongly the relative angular beam width $\sigma$ can change in anisotropic media, we study also the visualized picture of the surface spin wave beam propagation for the geometry, where the relative angular beam width $\sigma$ has high value $\sim 2$. As it may seem from fig. 3(b), geometries characterized by the value $\sigma \sim 2$ can be realized at angles $\varphi$ lying near angles of cutoff $\varphi_{cut}$, but these geometries cannot be realized because it is impossible to excite spin waves with very large value of the wave number $k_0$. However, the value $\sigma \sim 2$ appears also in the geometries, where the surface spin wave is excited by a linear transducer oriented closely to the vector $\mathbf{H}_0$, i.e., at $\varphi_0 \sim 0$ (fig. 3(b)). Below we describe the beam propagation for the most widely used geometry where the transducer is oriented along vector $\mathbf{H}_0$. The superposition of both amplitude and phase distributions for this geometry is shown in fig. 6 for spin wave frequency $f_0 = 3242$ MHz, $k_0 = 110.8$ cm$^{-1}$ ($\lambda_0 = 567$ $\mu$m) and $\lambda_0/D = 0.113$.

As one can see from fig. 6, the maximal part of the spin wave energy is transferred along the group velocity vector $\mathbf{V}_0$ in the form of the gradual widening main beam, having angular width $\Delta \psi_{exp} = 12.9^\circ$ (in fig. 6 the brightest area located along the $y$-axis corresponds to the main beam). The experimental value $\Delta \psi_{exp}$ is measured for the part of the beam lying at interval $y < 22$ mm. At $y > 22$ mm the amplitude of the beam is small and it is hard to analyse the amplitude distribution in the plane of a ferrite film with good accuracy. Note that a little part of the spin wave energy spreads on the whole area located between two straight lines corresponding to the group velocity cut-off angles $\psi_{1cut}$ and $\psi_{2cut}$ (fig. 6). Large deep areas located below these straight lines correspond to the ferrite film regions in which the spin wave cannot exist. As is well known, in two-dimensional anisotropic structures in which the wave’s ID are similar to hyperbolas (as for surface spin waves in fig. 2), the wave vector $\mathbf{k}$ cannot be oriented in any direction of the structure plane. So, two ranges of forbidden wave vector orientations and corresponding two ranges of forbidden group velocity vector orientations (that are determined by the normal to the ID) appear in the plane of such structures, i.e., the wave cannot have the wave vector orientation $\varphi$ or group velocity vector orientation $\psi$ from these ranges of angles (for more details, see refs. [24,28] and sect. 6.3 in ref. [5]).

The brightest area near the $y$-axis in fig. 6 corresponds to the greatest maximum of the magnetic potential distribution. On the contrary, darkest narrow angle sectors in fig. 6 are located along the angles, at which the magnetic

As can be seen, the measured value $a = 0.17$ dB/mm fits well into the previously obtained amplitude attenuation range. At the same time a more accurate comparison with the results from ref. [26] (for example, a comparison of values $a$ obtained at the same wave number $k$) will be incorrect. Since the main factor determining the amplitude attenuation $a$ is the magnitude $V$ of the spin wave group velocity, then we can compare values $a$ only for the waves with the same values $V$. However, for the fixed wave number $k$, the value $V$ for a superdirectional beam formed by the wave with non-collinear orientation of vectors $\mathbf{k}$ and $\mathbf{V}$ is much smaller than the value $V$ for the spin wave with collinear orientation $\mathbf{k}$ and $\mathbf{V}$ from ref. [26].

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It is usually assumed that if the exciting linear transducer is oriented parallel to the vector $\mathbf{H}_0$, a surface spin wave with collinear orientation of the vectors $\mathbf{k}$ and $\mathbf{V}$ is excited in a ferrite film and both $\mathbf{k}$ and $\mathbf{V}$ vectors are directed exactly along the optical axis $y$ (named also axis of collinear propagation). However, spin wave fronts in fig. 6 are slightly inclined with respect to the transducer line and the beam path (location of the greatest beam maximum) is only approximately directed along the $y$-axis — in fact the inclination of the beam path to the $y$-axis is about $5^\circ$. This inclination arises because at $\sim 3$ GHz (electromagnetic wavelength in vacuum $\sim 10$ cm) there is a small phase difference between the initial and final points of the exciting linear transducer (the distance between these points is $5$ mm) and this phase difference leads to certain inclinations for both wave vector $\mathbf{k}$ and group velocity vector $\mathbf{V}$ from the normal to the exciting transducer line. Thus, strictly speaking, the linear transducer is not a cophased exciter at microwave waves.

The comparison of parameters for the spin wave beam in figs. 4 and 5 shows that the beam in fig. 4 almost does not change its width along its whole trajectory $(\Delta \psi_{\exp} = 0.4^\circ$ and $\Delta \psi_{\exp} = 0.03)$. Quite the contrary, the spin wave beam in fig. 6 is significantly expanded $(\Delta \psi_{\exp} = 12.9^\circ$ and $\sigma_{\exp} = 2$), despite the fact that for this beam the ratio $\lambda_0/D = 0.113$ is twice smaller than the ratio $\lambda_0/D = 0.222$ for the beam in fig. 4. The experimental results are in good agreement with theoretical investigations, calculations and formulas in the works [8, 19].

Mention must be made that superdirectional beams of the backward spin waves was predicted [13] and observed recently [17] in the free ferrite slab, too.

**Conclusions.** In summary, we investigate experimentally the diffraction patterns of surface spin waves excited by an arbitrarily oriented linear transducer in a tangentially magnetized ferrite film for the case in which the transducer length $D$ is much larger than the wavelength $\lambda_0$. In the study we used the scanning probe method, that gives the possibility to visualise the amplitude and phase distributions of the spin wave along the film surface. The angular beam width of the spin waves is measured experimentally and is calculated theoretically by means of the general formula derived in [8] for the angular beam width in anisotropic media. It is proved experimentally that as distinct from the beams in isotropic media the angular beam width $\Delta \psi$ of the surface spin wave is not a constant value: it depends on the transducer orientation $\varphi_0$ and can take values greater or smaller than the ratio $\lambda_0/D$ (where $\lambda_0$ is the excited wavelength and $D$ is the exciter length). Moreover, we found such experimental parameters and transducer orientation, at which the angular beam width $\Delta \psi$ is about zero (it means physically that the beam retains its absolute width during propagation). This phenomenon occurs when the following conditions are satisfied simultaneously: 1) the excitation of a very narrow spectrum of wave vectors near a certain
value $k_0$ takes place (that is possible, for example, if the wavelength $\lambda_0 = 2\pi/k_0$ is much less than the transducer length $D$); 2) the wave vector orientation $\varphi_0$ (or the transducer orientation) should correspond to the ID inflection point (where $d\psi/d\varphi = 0$).

Thus, it is shown that such phenomenon as “superdirectional propagation of the waves” exists in Nature. It is also evident that the well-known Rayleigh criterion used in isotropic media cannot be used to estimate the angular width of spin wave beams. An example of the surface spin wave diffraction gives us hope that the same diffractive phenomena can take place in the other anisotropic media and structures and that the use of superdirectivity will help to create new devices with a much higher resolving power.

In addition it was found that a linear transducer oriented parallel to the external constant magnetic field $H_0$ excites the surface spin wave with wave vector $k$ and group velocity vector $V$ which are only approximately directed along the perpendicular axis to the vector $H_0$, since there is a small phase difference between the initial and final points of the linear transducer.

The experimental results are in good agreement with theoretical investigations, predictions, calculations and formulas on the basis of the works [8,19].

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