05,13

Linear dynamics of spin waves in an array of YIG waveguides

© A.B. Khutieva, E.N. Beginin, S.E. Sheshukova, A.V. Sadovnikov

Saratov National Research State University,
Saratov, Russia

E-mail: abkhutieva@gmail.com

Received July 31, 2021
Revised July 31, 2021
Accepted August 8, 2021

The features of spin-wave transport in a system of coupled magnetic microwaveguides with perpendicular magnetization relative to the longitudinal axis of the system are considered. In this case, the system has uniaxial anisotropy, the horizontal and vertical coupling coefficients have different signs, and the isofrequency surfaces have a „saddle"shape. In the propagation of transversely limited beams of spin waves, the type of curvature of the wave fronts is determined by the direction of wave propagation relative to the external magnetic field.

Keywords: spin waves, magnonics, microwaveguides, lateral structures.

DOI: 10.21883/PSS.2022.14.54337.181

1. Introduction

Magnons, that are quanta of spin-wave excitations, can be used as carriers of information signals at frequencies from several GHz to hundreds GHz [1]. Magnon networks (MN), consisting of coupled systems of spin microwaveguides based on yttrium iron garnets (YIG) films, can be used for information processing and at the same time provide the process integration with the existing architecture of CMOS [2]. For instance, in the work [3] it was shown, that three-dimensional (3D) magnon crystal in a shape of meander can provide propagation of spin waves in all spatial dimensions.

In this work we study influence of dipole bond of magnon microwaveguides for implementation of vertical and lateral magnon transport. Coupled waves method was used for studying the dynamics of spin waves (SWs) propagation in a system of YIG waveguides.

2. System of coupled waveguides and numerical modeling

It is known, that dynamics of propagation of different physical nature waves in the systems, consisting of identical coupled waveguides, can be described, for instance, based on the coupled waves method [4,5] in nearest neighbors approximation. The system of the first order differential equations is used in numerical modeling of spin transport in a system of dipole coupled magnetic microwaveguides, written as [6]:

$$dA_{mn}/dz = i\beta A_{mn} + iC_v(A_{m+1,n} + A_{m-1,n}) + iC_g(A_{m,n+1} + A_{m,n-1}), \qquad (1)$$

where: A_{mn}— amplitude of a spin wave in a waveguide, propagating in z direction, suffix numbers — number of a waveguide along horizontal (m) and vertical (n) directions, respectively; β — wave number of a spin wave at frequency f in a single insulated waveguide; C_v and C_g — vertical and horizontal coupling coefficients, respectively. Spin waves dynamics in the examined system are defined with values of β, C_v, C_g, which, in their turn, depend on orientation of a static magnetic field relative to longitudinal direction z.

In case of orientation of external magnetic field along z axis, the reverse volume SWs [7] can propagate in magnetic microwaveguides and the examined system will be like a system of coupled optical waveguides with positive values of coupling coefficients C_g and C_v [6].

The system becomes anisotropic at static magnetic field orientation in (xy) plane. For instance, at magnetization of the system along x axis, the dispersion characteristics of flat SWs, propagating in (xz) plane, depend on frequency f and direction of a wave vector relative to magnetic field direction [7]. Dispersion characteristics of the flat SWs, propagating in (yz) plane, depend on frequency only. I.e. the system of coupled magnetic microwaveguides is a medium with uniaxial anisotropy, set by the external magnetic field direction. Values of these coefficients depend in geometry and period of microwaveguides lattices and dispersion characteristics of $\beta(f)$ spin waves.

Figure 1 shows the scheme of the examined system, consisting of identical magnetic YIG microwaveguides with width c and thickness d. Distances between edges of adjacent waveguides along x and y axes are equal to a and b, respectively. Spatial periods of the system along the corresponding directions are equal to $d_x = a + c$ and $d_y = b + d$. Total length of the waveguides system is l. Foreign sources of dynamic magnetic fields, for instance, in the form of microstrip antennas, were set for selective generation of spin waves in individual waveguides. The whole system is put into external static magnetic field H, directed along x axis

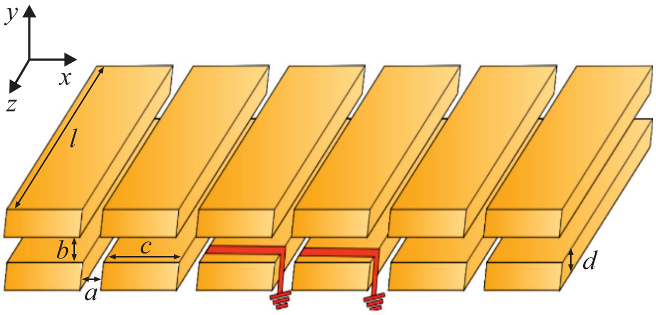

Figure 1. Scheme of the examined system of the coupled magnetic microwaveguides.

Let's examine the influence of signs of coupling coefficients C_v and C_g on a shape of isofrequency surfaces of spin waves in infinite two-dimensional microwave lattice. Let's imagine a wave process in a waveguides lattice in the form of flat waves

$$A_{mn}(k_x, k_y) = A_0 \exp\big(i(k_x m d_x + k_y n d_y)\big). \quad (2)$$

Substituting (2) in (1), we obtain the dispersion relation for flat SWs in infinite two-dimensional lattice as

$$k_z(k_x, k_y) = \beta + 2C_g \cos(k_x d_x) + 2C_v \cos(k_y d_y). \quad (3)$$

Figure 2 shows the results of calculations at a fixed frequency f of dependencies of $k_z(k_x, k_y)$ (isofrequency

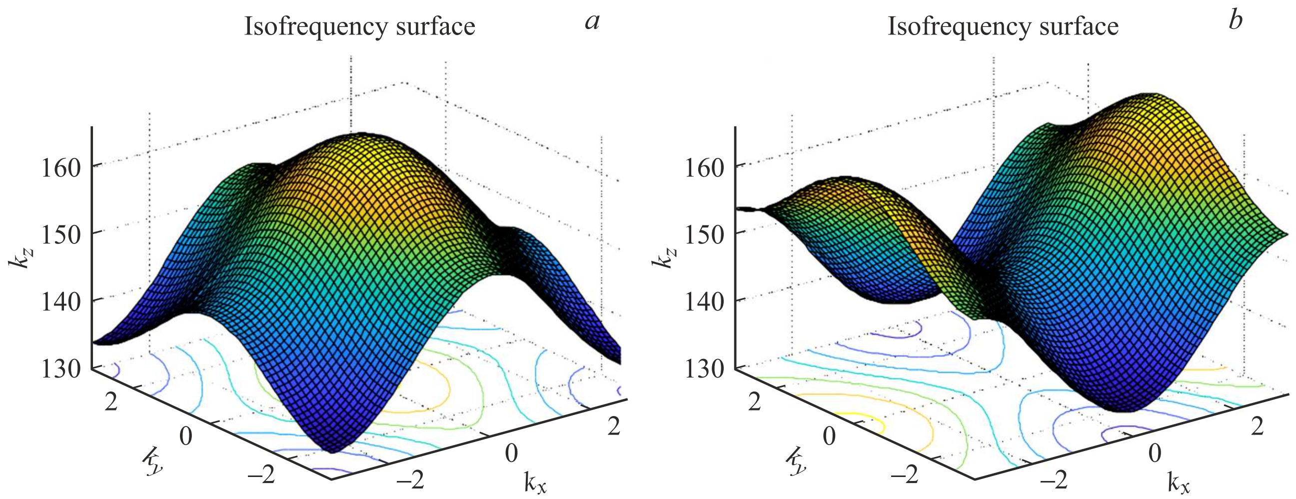

Figure 2. Isofrequency surfaces of spin waves at $\beta = 150\,\mathrm{cm}^{-1}$ in an infinite lattice of the waveguides: *a* — $C_v = 3.0\,\mathrm{cm}^{-1}$, $C_g = 5.0\,\mathrm{cm}^{-1}$; *b* — $C_v = 3.0\,\mathrm{cm}^{-1}$, $C_g = -5.0\,\mathrm{cm}^{-1}$.

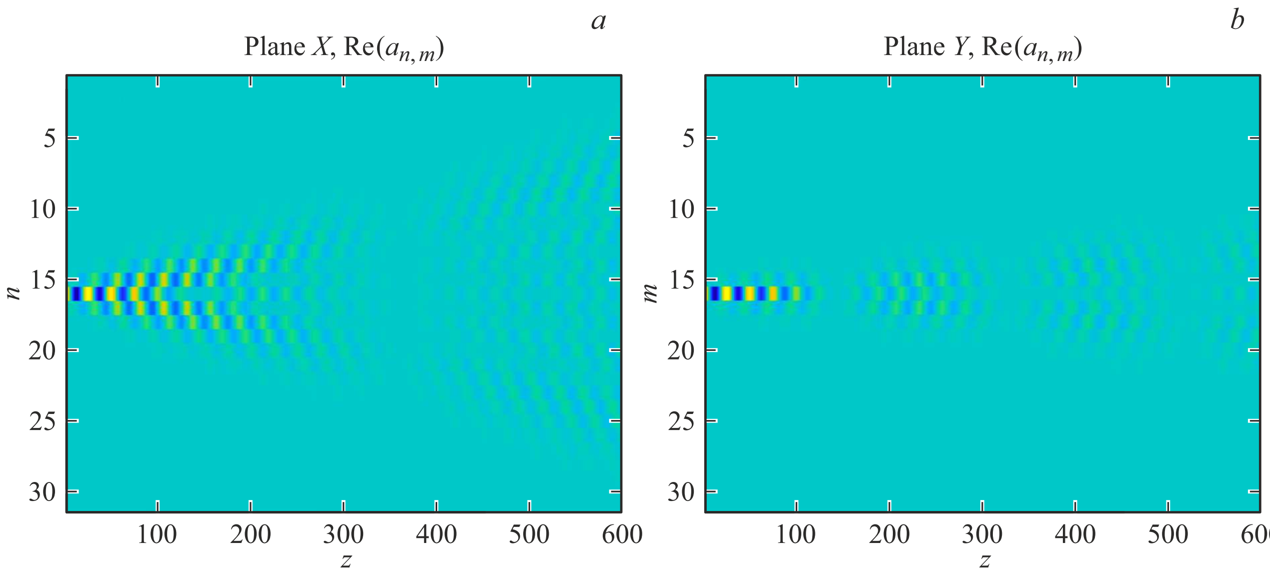

Figure 3. Spatial distributions of spin waves amplitudes in two-dimensional waveguides lattice at $\beta = 150\,\mathrm{cm}^{-1}$, $C_v = 2.0\,\mathrm{cm}^{-1}$, $C_g = -5.0\,\mathrm{cm}^{-1}$: *a* — *xz* plane, *b* — *yz* plane.

surfaces) at various signs of the coupling coefficients. If the coupling coefficients have the same sign (Fig. 2, a), the isofrequency surface has a shape of a „shaft" with maximum of a wave number k_z in the point with coordinates (0,0) and is similar to isofrequency surfaces in case of optical waveguides. If the coefficients have different signs (Fig. 2, b), the isofrequency surface has a shape of a „saddle" with minimum of a wave number k_z in the point with coordinates (0,0). Such shape of isofrequency surface is caused by a form of dispersion characteristics of surface SWs, propagating at various angles to static magnetic field direction [7].

Let's examine the features of spin wave beams formation in infinite two-dimensional lattice of waveguides at excitation of a single waveguide (point excitation source). Figure 3 shows the spatial distributions of spin waves amplitudes in two mutually perpendicular planes (xz) and (yz), crossing the excitation source and having different signs of the coupling coefficients $C_v > 0$ and $C_g < 0$. As seen from the presented results, the diffraction blooming of spin waves beam due to a bond between the adjacent waveguides is observed. At the same time, the shapes of wave fronts in two mutually perpendicular planes are different: in (xz) plane relative to the source the front is concave, while in (yz) plane — convex. The specified features of dispersion characteristics of SWs result in formation of complex wave patterns in the systems of coupled magnetic microwaveguides.

3. Conclusion

Thus, the performed studies of linear dynamics of spin waves in a system of coupled YIG waveguides showed, that at the system magnetization perpendicular to SW propagation direction, it has uniaxial anisotropy and within the coupled waves method can be described by introduction of positive and negative coefficients of horizontal and vertical bond. At propagation of transversely limited beams of spin waves, the type of curvature of the wave fronts (concave, convex) is determined by the direction of SW propagation relative to the external magnetic field. The obtained results can be used for elaboration of spin-wave transport nature in arrays of micro- and nanoscale magnetic structures.

Funding

The work was carried out with support from the Russian Foundation for Basic Research (No. 19-29-03034) and the grant of the President of the Russian Federation (MK1870.2020.9).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.V. Kruglyak, S.O. Demokritov, D. Grundler. J. Phys. D **43**, 264001 (2010).
[2] A.V. Sadovnikov, S.A. Nikitov, E.N. Beginin, A.V. Sadovnikov, E.N. Beginin, S.E. Sheshukova, Yu.P. Sharaevskii, A.I. Stognij, N.N. Novitski, V.K. Sakharov, Yu.V. Khivintsev, S.A. Nikitov. Phys. Rev. B **99**, 054424 2019.
[3] G. Gubbiotti, A. Sadovnikov, E. Beginin, S. Nikitov, D. Wan, A. Gupta, S. Kundu, G. Talmelli, R. Carpenter, I. Asselberghs, I.P. Radu, C. Adelmann, F. Ciubotaru. Phys. Rev. Appl. 2021.
[4] A. Yariv. IEEE J. Quantum Electron. **9**, *9*, 919 (1973).
[5] W.-P. Huang. J. Opt. Soc. Am. **11**, *3*, 963 (1964).
[6] F. Lederer, G.I. Stegeman, D.N. Christodoulides, G.A. Assanto, M. Segev, Y. Silberberg. Phys. Rep. **463**, *1–3*, 1 (2008).
[7] D. Stancil, A. Prabhakar. Spin Waves: Theory and Applications. Springer, N.Y. (2009). 346 p.