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Induction of Superlattices for Canalized Waves in Magnetically Ordered Media by External Waves

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Abstract—Possible schemes for creating superlattices for channeled waves in magnetically ordered media by modulating their parameters by extraneous waves are discussed.

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INTRODUCTION

In modern solid state physics, whose father is rightly considered the French physicist Brillouin [1, 2], there are many directions, among which wave processes can be distinguished in media with spatial or spatiotemporal periodicity of properties. Spatial periodicity can be intrinsic (in crystals) or embedded, created by a periodic external action (the so-called superlattices). Space-time periodicity arises due to the modulation of the parameters of the medium when an external harmonic wave passes through it. As examples of studying the behavior of electromagnetic, spin, elastic, and hybrid waves in such modulated media, one can point to the results presented in [3–6].

Various media with superlattices are currently of particular interest. Noting this, many question the assertion that it only began at the end of the 20th century. Similar studies have been carried out before, but the results in this case were presented in a different way. The most striking example is Rayleigh's work published almost 150 years ago in which among the problems touched upon is the propagation of waves through a medium with an embedded periodic structure [7]. However, it took about 100 years, thanks to the publications of a number of authors [8, 9], for such media to acquire the name of photonic crystals, since electromagnetic waves in such media clearly manifest the properties of quasiparticles. By analogy, a similar "quasi-particle" terminology has now been extended to other wave-guiding media with superlattices included in the group of metamaterials, using the expressions "phononic crystals," "plasmon crystals," "magnon crystals," etc.

To create such "crystals" with an embedded spatial periodicity, used in specific devices on waveguide media, a wide variety of methods are used, the choice of which depends on the purpose of the device being created, the material of the medium, the required dimension of the "superlattice", the type and range of operating waves, etc. Information has also appeared on the implementation of magnetoplasmonic and magnonic crystals in magnetically ordered film media [10], as well as photonic crystals in paramagnetic films with a large Verdet constant using external diffraction gratings [11].

1. OBJECTIVE AND CONTENT

The objective of this study is to consider and compare two possible schemes for the formation of superlattices for channeled working waves in homogeneous magnetically ordered media. Both schemes use modulation by external waves to create the necessary periodicity of the properties of the media.

To describe the first scheme, let us turn to the results of [4], where for the case of a uniformly magnetized isotropic ferromagnet with spatiotemporal modulation of the internal magnetic field of type

$$H_{\mathrm{d}} \cos(\Omega t - \chi z_{\mathrm{s}})$$

the procedure for finding a solution in Cartesian coordinates $(x_{\mathrm{s}}, y_{\mathrm{s}}, z_{\mathrm{s}})$ of a dynamic equation for canalized spin waves of the following form was presented:

$$dm_{\mathrm{s}}/dt = i[\omega_{\mathrm{s}} + \gamma H_{\mathrm{d}} \cos(\Omega t - \chi z_{\mathrm{s}})] m_{\mathrm{s}}, \qquad (1)$$

where $m_{\mathrm{s}} = m_{x_{\mathrm{s}}} + i m_{y_{\mathrm{s}}}$ is the complex amplitude of the variable part of the magnetization, $\omega_{\mathrm{s}} = \gamma(H_0 + Dk^2)$, k is the wavenumber of the spin wave, γ is the gyromagnetic constant, H_0 is the bias field, D is the inhomogeneous exchange interaction constant, and Ω and χ are the frequency and wave number of the modulating wave with the amplitude of magnetic field strength H_d.

It was assumed that the spin waves and the modulating wave propagate along the z_s-axis, the constant part of the magnetization vector, the intensity of the modulating magnetic field, and the intensity of the bias field are oriented along the same axis, and the modulus of the latter significantly exceeds the saturation magnetization of the medium.

The solution of Eq. (1) can be represented as series

$$m_k = \sum_{n=-\infty}^{n=+\infty} B_n \exp\{i[(\omega + n\Omega)t - (k + n\chi)z_k]\}, \quad (2)$$

where ω is the frequency of the spin wave. Substitution (2) into (1) and selection of terms with the same space-time dependence leads to an infinite system of recurrence relations in form

$$y_h B_{n-1} - \left[(y' + n) - C(x' + n)^2\right] B_n + y_h B_{n+1} = 0, \quad (3)$$

where dimensionless variables are introduced

$$x' = k/\chi, \quad y = \omega/\Omega, \quad y' = (\omega - \omega_H)/\Omega$$

and parameters

$$y_0 = \omega_H/\Omega, \quad y_h = \omega_h/2\Omega, \quad \omega_H = \gamma H_0,$$
$$\omega_h = \gamma H_d, \quad C = \gamma D\chi^2/\Omega.$$

Equating the determinants of system (3) to zero, we obtain the relation

$$\begin{aligned}&\Delta_n - 1/(\Lambda_{n-1} - (1/\Lambda_{n-2} - (1/\Delta_{n-3} - \ldots)))\\ &- 1/(\Delta_{n+1} - (1/\Delta_{n+2} - (1/\Delta_{n+3} - \ldots))) = 0,\end{aligned} \quad (4)$$

where

$$\Delta_n = -\left[(y' + n) - C(x' + n)^2\right]/y_h,$$

with which numerical methods can be used to determine the form of dispersion curves in dimensionless normalized coordinates $y' = f(x')$. It turns out that the dispersion dependences have an infinite number of branches, which are located on the plane near the so-called reference curves defined by equations

$$(y' + n) - C(x' + n)^2 = 0. \quad (5)$$

A reference curve with $n = 0$ corresponds to the dispersion curve for spin waves in an unmodulated medium, the rest (for other values n) are obtained by shifting this curve along the coordinate axes by any integer of any sign. Blocking bands appear near the intersection points of any reference curves (the most pronounced at the intersection with the dispersion curve with $n = 0$), where system of equations (4) has no solutions for real values of the wave vector.

Inside the nth amplitude stop band of zero and nth harmonics become comparable in magnitude and significantly exceed the amplitudes of the other harmonics. When the directions of propagation of the modulating wave and the prevailing harmonics coincide, poundings occur between the latter; conversion of direct waves into reverse ones with a shift in frequency and wave number. Magnetically ordered media with occlusion bands induced by an external modulating wave for channeled spin waves are classified as dynamic (or tunable) magnonic crystals (see, for example, [5, 6, 12]).

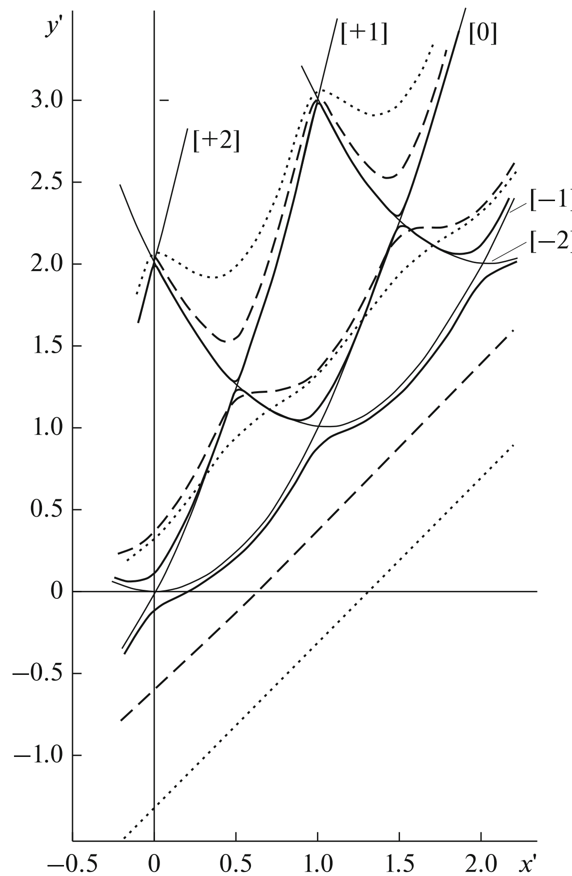

Fig. 1. Dispersion curves for spin waves in a medium with spatiotemporal periodicity at $y_h = 0.1$ (thick solid lines), $y_h = 0.5$ (dashed lines), and $y_h = 1.0$ (dotted lines); reference curves (thin solid lines) are marked with numbers in brackets.

In Fig. 1, which is an identical photographic copy of Fig. 1 in [4], dimensionless variables (x', y') presents the results of a numerical calculation of dispersion curves in a medium at $C = 1$ for three parameter values y_h, which is the modulation index. All curves in the normalized coordinates used are periodic with respect to any straight line with a slope equal to 1.

In the second scheme for the implementation of magnonic crystals, the modulation of the parameters of the working media is also used, but only under the action of electromagnetic waves in the light range. It is known, for example, that in epitaxial films of yttrium iron garnet containing silicon, under certain conditions, a noticeable (up to 30%) change in the induced magnetic anisotropy constant under the action of polarized light is observed; the cubic anisotropy constants change little in this case (see, for example, [13]). Effects similar to those described can be used to create "nontunable" magnonic crystals. Indeed, if a collimated beam of light is passed through a conventional diffraction grating and then directed through a lens to the surface of a magnetic film placed in the focal plane of the lens, then a sequence of regions alternating with each other with an increased and decreased induced magnetic anisotropy constant will be formed inside the film, which will lead to periodic modulation of the strength of the internal magnetic field. To ensure the possibility of the existence of a magnonic crystal, it is necessary that such an alternation occurs with a period much greater than the length of the channeled spin wave at the operating frequency.

CONCLUSIONS

When comparing the described methods for creating magnonic crystals, preference should be given to the first scheme, despite the fact that the light-induced method in the future may provide an advantage over others, since it is local, remote, and retains its efficiency even when using ultrashort pulses. Unfortunately, the practical implementation of this advantage is complicated by the fact that a noticeable change in the magnetic anisotropy constants is observed only at sufficiently low temperatures and even under these conditions is accompanied by strong thermomagnetic annealing [13]. And in favor of the first scheme is also the fact that the appearance of a non-transmission band for surface spin waves in films of yttrium iron garnet due to the use of spatiotemporal modulation of the medium was confirmed experimentally [6].

Encouraging for the second scheme, however, is the fact that a report has recently appeared on the possibility of the existence in centroantisymmetric antiferromagnets of an inhomogeneous light-induced flexoantiferromagnetic effect, in which the light field shifts the Néel point, renormalizes the anisotropy constants, and creates an additional magnetic field [14]. When using this effect, the depth of light-induced modulation of the parameters of the medium increases not only due to an increase in the power of the light sources used, but also due to a decrease in the thickness of the light beam, since the gradient of the light electric field increases at its boundary. The described possibility of enhancing light-induced effects deserves special attention, since at present, there has been a marked increase in interest in the practical use in microelectronics and spintronics (for example, in spin valves) of antiferromagnets, since it was found that spin waves in such media have the ability to carry a spin-polarized current.

CONFLICT ON INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. L. Brillouin, *Wave Propagation in Periodic Structures. Electric Filters and Crystal Lattices* (McGraw-Hill, New York, 1946).
2. L. Brillouin and M. Parodi, *Propagation des Ondes dans les Milieux Periodiques* (Masson, Paris, 1956; Inostrannaya Literatura, Moscow, 1959).
3. E. S. Cassedy and A. A. Oliner, Proc. IEEE **51**, 1342 (1963).
4. N. N. Kiryukhin and F. V. Lisovskii, Fiz. Tverd. Tela (Leningrad) **10**, 709 (1968).
5. R. G. Kryshtal and A. V. Medved, Appl. Phys. Lett. **100**, 192410 (2012).
6. R. G. Kryshtal and A. V. Medved, J. Magn. Magn. Mater. **491**, 165599 (2019).
7. J. W. S. Rayleigh, Philos. Mag. **24**, 145 (1887).
8. E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
9. S. John, Phys. Rev. Lett. **58**, 2486 (1987).
10. T. Bud'ko, N. Novitskii, and A. Stognii, Nauka i Innovatsii, No. 4, 12 (2017).
11. E. A. Bezus, V. I. Belotelov, L. L. Doskolovich, and A. K. Zvezdin, Komp. Opt. **35**, 432 (2011).
12. A. V. Chuma1, T. Neumann, A. A. Serga, et al., Phys. Rev. Lett. **58**, 2486 (1987).
13. V. G. Veselago, I. V. Vladimirov, P. A. Doroshenko, and L. S. Setchenkov, Fiz. Tverd. Tela (Leningrad) **148**, 272 (1986).
14. A. F. Kabychenkov and F. V. Lisovskii, Tech. Phys. **92** (3), 453 (2022).