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Tunneling magnon flow across the terminated ferromagnetic chain

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A mechanism is proposed for transferring magnon energy from one ferromagnet to another by tunneling magnons through a bridging ferromagnetic wire that connects ferromagnets. In the framework of the model of Bose gas for the magnons, expressions are found for the power of the transferred magnon energy from a ferromagnet having a higher temperature to a colder ferromagnet. It is shown how the efficiency of tunneling transport depends on the parameters of exchange interactions in the "ferromagnet–wire–ferromagnet" system, the single-ion anisotropy of the structural units of the system, and the magnetic field. As an example, the role of single-ion anisotropy in the formation of resonant and non-resonant transmission of magnons between ferromagnets and adjacent wire terminal units is shown, which accordingly significantly enhances or weakens the tunneling flow of magnons from one ferromagnet to another.

Keywords: tunneling magnon, ferromagnetic wire, single-ion anisotropy, paramagnetic ions.

1. Introduction

The use of uncharged elementary excitations as information carriers opens up wide possibilities for quantum communication. Of particular interest are magnons, which are spin excitations of paramagnetic ions in magnetically ordered structures [1–3]. In recent years, in connection with the miniaturization of the element base of transmitting and recording devices, interest in studying the mechanisms of generation, transport and fixation of magnons in hybrid quantum systems has especially increased [4–6]. Particular attention was paid to nonconducting single-molecule magnets and spin wires [7–9]. The prospect of using such magnetic insulators lies in the fact that they manifest specific magnon transmission. At present, various methods for generating magnons in heterostructures have been developed. To this end, the standard method of thermal excitation, nonlocal transport of quasi-acoustic magnons [10], and also parametric coherent pumping [11–13] are used. The latter method is especially effective for generating magnons in nanoscale magnetic structures where the creation of microwave cavity modes is possible [14–17].

One of the important low-dimensional magnetically ordered structures is ferromagnetic chain inserted between magnetic dielectrics (Fig. 1). A study of the efficiency of magnon transfer through such chain depending on the number of repeating paramagnetic units of the chain allows us to clarify the mechanisms of magnon flow formation through extended quasi-one-dimensional magnetic structure and thereby evaluate the efficiency of information transfer between spaced magnetic centers.

In this work, we carry out a theoretical study of the tunnel transport of magnons between ferromagnets A and B jointed by a ferromagnetic wire (AWB-system, Fig. 1). The directed transport of magnons in the AWB system can be due to many reasons, for example, the difference in the magnetic structure of A and B or the nonidentical pumping of magnons in these magnets. Here we will consider the formation of a magnon tunneling flow caused by a temperature gradient between spaced ferromagnets. This leads to

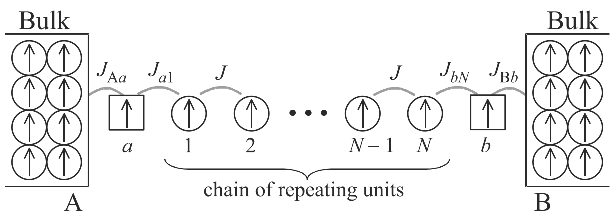

Fig. 1. Magnon transfer device: a ferromagnetic wire is connected to the ferromagnetic insulators A and B through the paramagnetic terminal units a and b. Parameters $J_{Aa(Bb)}$ and $J_{a1(bN)}$ characterize the exchange coupling of the spins of the terminal units with the corresponding spins of the contact units of ferromagnets and the spins of the edge units of the paramagnetic chain consisting of N repeating units.

the specific Seebeck effect. In contrast to the spin-dependent Seebeck effect associated with the movement of spin-polarized electrons from one magnetic metal electrode to another [18], the magnon-dependent Seebeck effect reflects the movement of uncharged excitations between ferromagnetic dielectrics.

2. Model and theory

The tunneling transfer of magnons between ferromagnetic contacts, mediated by a ferromagnetic chain, has already been considered in [19]. An analytical expression was found for the magnon transmission function. The behavior of this function is shown to be determined by the parameters of the exchange interaction in the wire and the length of the internal part of the wire. In this paper, we consider a possible mechanism for coherent transmission of magnon energy across a ferromagnetic wire under conditions of non-resonant and resonant transfer of a magnon between ferromagnets and the terminal units of a wire.

We will estimate the power of the magnon energy W carried by the wire connecting the magnets A and B, which are at temperatures $T_{\rm A}$ and $T_{\rm B} (< T_{\rm A})$, respectively.

In line with the definition, we have

$$W = -\sum_k E_{{\rm A}k}\dot{n}_{{\rm A}k}, \tag{1}$$

where $n_{rk} = \langle b_{rk}^+ B_k \rangle$ is the average number of magnons in the rth ferromagnet. (Operator $b_{rk}^+ (b_{rk})$ corresponds to the creation (annihilation) of a magnon with energy E_{rk} and wave vector k). The change in $n_{{\rm A}k}$ per unit time is described by the kinetic equation

$$\dot{n}_{{\rm A}k} = -\sum_{k'} [\mathcal{K}_{{\rm A}k\to{\rm B}k'} n_{{\rm A}k} - \mathcal{K}_{{\rm B}k'\to{\rm A}k} n_{{\rm B}k'}], \tag{2}$$

with

$$\mathcal{K}_{rk\to r'k'} = \frac{2\pi}{\hbar} |V_{r'k',rk}|^2 f_{rk} \delta(E_{rk} - E_{r'k'}) \tag{3}$$

being the rate characterizing the single-step hopping of a magnon with the wave vector k from the ferromagnet r to the ferromagnet r'. Quantity

$$f_{rk} = [\exp(E_{rk}/T_r) - 1]^{-1} \tag{4}$$

is the equilibrium magnon distribution function in the rth ferromagnet at temperature T_r.

Kinetic equation (2) is valid in the magnon-gas approximation, when the inequality

$$\sum_k n_{rk} \ll N_r S_r \tag{5}$$

is satisfied [2]. Here, N_r is the number of repeating paramagnetic units forming the rth ferromagnetic structure. Spin value of each unit is S_r. Transition matrix element

$$V_{r'k',rk} = \langle r'k' | V_{\rm tr} G(E) V_{\rm tr} | rk \rangle \tag{6}$$

characterizes a distant coupling between excited states $|rk\rangle = b_{rk}^+ |0\rangle$ and $|r'k'\rangle = b_{r'k'}^+ |0\rangle$ belonging to varies ferromagnets. (Symbol $|0\rangle$ denotes the vacuum state for magnon). The transition occurs at the energy $E = E_{rk} = E_{r'k'}$. Following the results presented in [19], we define the Green operator

$$G(E) = \frac{1}{E - H_{\rm AWB}^{\rm eff}}, \tag{7}$$

with use of the effective AWB Hamiltonian

$$H_{\rm AWB}^{\rm eff} = \sum_{r={\rm A,B}} H_r + \sum_{l=a,b} H_l^{\rm eff} + H_{\rm chain}. \tag{8}$$

Here, the magnon Hamiltonian of the rth ferromagnet appears in the form

$$H_r = \sum_k E_{rk} b_{rk}^+ b_{rk}, \tag{9}$$

where $E_{rk} = E_r + J_r S_r z_r (1 - \gamma_{rk})$. Quantity $E_r \equiv E_{rkr=0} = g_r \mu_B H_r + D_r (2S_r - 1)$ is the lowest magnon energy of a bulk ferromagnet in the magnetic field H_r directed along the Z axis whereas γ_{rk} is the structure factor. The g-factor, the Bohr magneton and the constant of single-ion magnetic anisotropy are denoted by g_r, μ_B and D_r, respectively. Parameter J_r characterizes the exchange interaction between the nearest pair of paramagnetic ions, z_r is the number of nearest paramagnetic ions with respect to the given paramagnetic ion. The Hamiltonian of the spin excitation of the lth terminal unit of the wire is presented in an effective form taking into account the effect of the bulk ferromagnet A(B) on spin excitation in the adjacent terminal unit l. The Hamiltonian reads

$$H_l^{\rm eff} = \mathcal{E}_l b_l^+ b_l, \quad (l = a, b), \tag{10}$$

where $\mathcal{E}_l = E_l - i\Gamma_l(E)/2$. The first term, $E_l = g_l \mu_B H + D_l(2S_l - 1) + \beta_{rl}\sqrt{S_r/S_l} + \beta_{ln}\sqrt{S/S_l}$ is the energy of the localized spin excitation. Quantities

$$\beta_{rl} = J_{rl}\sqrt{S_r S_l}(\delta_{r,A}\delta_{l,a} + \delta_{r,B}\delta_{l,b}),$$

$$\beta_{ln} = J_{1n}\sqrt{S_l S}(\delta_{l,a}\delta_{n,1} + \delta_{l,b}\delta_{n,N})$$

are expressed through the parameters J_{rl} and J_{1n} that characterize the exchange interaction of the terminal spin S_l with the neighboring spins S_r and S belonging to the bulk ferromagnet and the ferromagnetic chain, respectively. The imaginary addition to the energy, $\Gamma_l(E)/2$, appeared due to the off-diagonal interaction

$$V_{rl} = \sum_k [\beta_{l,rk} b_l^+ b_{rk} + \beta_{l,rk}^* b_{rk}^+ b_l] \tag{11}$$

of the terminal spin with the spins of a bulk ferromagnet. Note the definition of $\beta_{l,rk} = \beta_{rl} N_r^{-1/2} \exp(-ikr_l)$, valid for simple bulk crystal (r_l is the position of the surface unit that is in contact with the lth terminal unit of wire). Using the definition $\Gamma_l(E) = 2\pi \sum_k |\beta_{l,rk}|^2 \delta(E - E_{rk})$ and the expansion of the magnon energy around wave vector $k = 0$ we derive

$$\Gamma_l(E) = \frac{\beta_{rl}^2}{2\pi} \frac{(E - E_r)^{1/2}}{E_{rc}^{3/2}} \Theta(E - E_r), \qquad (12)$$

where $E_r = g_r \mu_B H_r + D_r(2S_r - 1)$ and $E_{rc} = 2\beta_r \equiv 2J_r S_r$.

In our model, the interaction of the terminal groups of the wire with the contact units of ferromagnets and the terminal units of the wire is considered as a perturbation. It is assumed that this interaction does not significantly affect the energies of delocalized magnons both in ferromagnets and a chain of repeating units. But we take this interaction into account in a fundamentally important factor (12).

The third term on the right part of Eq. (8) reads

$$H_{\text{chain}} = \sum_\lambda E_\lambda b_\lambda^+ b_\lambda. \qquad (13)$$

It refers to the Hamiltonian of the inner range of the wire. Proper energies of this Hamiltonian,

$$E_\lambda = E_c - 2\beta \cos\frac{\pi\lambda}{N+1}, \quad (\lambda = 1, 2, \ldots N), \qquad (14)$$

is the energy of spin excitation in the ferromagnet chain of N paramagnet units. Here, $E_c = g\mu_B H + D(2S-1) + 2\beta$ is the center of discrete magnon band of N levels and $\beta = JS$ is the parameter that characterizes the exchange coupling within the chain (cf. Fig. 2).

Transitions between the magnon states of the AWB system are realized due to interactions (11) and

$$V_{lc} = \sum_{\lambda=1}^{N} [\beta_{l\lambda} b_l^+ b_\lambda + \beta_{l\lambda}^* b_\lambda^+ b_l], \qquad (15)$$

where $\beta_{l\lambda} = \sum_n \beta_{ln} u_{n\lambda}$. Here, $u_{n\lambda} = (N+1)^{-1/2} \times \sin[n\lambda/(N+1)]$ is an element of the matrix U that transforms the localized excitation spin states of the chain into the delocalized magnon states. Interaction (15) is responsible for the transfer of spin excitation between the terminal units and the bridging ferromagnet chain.

The magnon pathway between bulk ferromagnets A and B is controlled by interactions (11) and (15). Therefore, taking into account expressions (7) and (8) for the Green operator, as well as the definition $V_{\text{tr}} = V_{rl} + V_{lc}$ for the transition operator, we can estimate the amount of energy transmitted by one tunneling magnon per time unit. To this end, we transform the expression (1) to the form

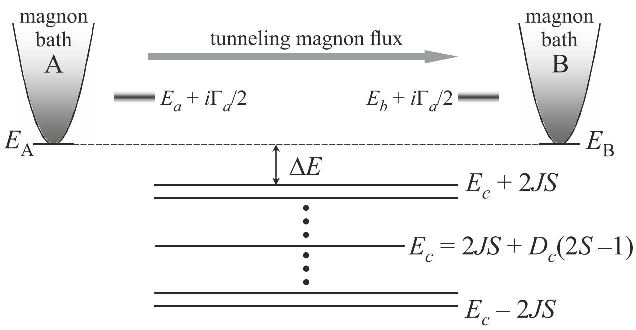

Fig. 2. Relative position of magnon energies in AWB-device. In the model of effective mass, the bottom of the magnon band in bulk ferromagnet corresponds to the energy $E_{A(B)}$. Energy level of the localized spin excitation of the terminal unit $a(b)$ is broadened by $\Gamma_{a(b)}/2$. The upper delocalized level of the discrete magnon band of the chain is separated from the lower part of the magnon energy of the bulk ferromagnet by the value ΔE.

$$W = \frac{1}{2\pi\hbar} \int_0^\infty dE\, E \Gamma_a(E) |G_{ab}(E)|^2 \Gamma_b(E) \times$$
$$\times (f_A(E) - f_B(E)), \qquad (16)$$

where $f_{A(B)}(E)$ and $\Gamma_l(E)$ are determined by the corresponding formulas (4) and (12). Quantity

$$G_{ab}(E) = \frac{\beta_{a1}\beta_{bN}}{(E - \mathcal{E}_a)(E - \mathcal{E}_b)} G_{1N}(E - E_c) \qquad (17)$$

is the matrix element of the wire's Green operator $G(E)$ [19,20]. The dependence of this value on the number of bridging units of the paramagnet chain is concentrated in the Green function $G_{1N} = \sum_\lambda u_{1\lambda} u_{n\lambda}^* / (E - E_\lambda)$ coupling the end units $n = 1$ and $n = N$. Its analytic form reads

$$G_{1N}(E - E_c) = \frac{\beta^{-1} \sinh[\zeta(E - E_c)/2]}{\sinh[\zeta(E - E_c)(N+1)/2]}, \qquad (18)$$

where

$$\zeta(E - E_c) = 2 \ln[\alpha + \sqrt{\alpha^2 - 1}] \qquad (19)$$

is the attenuation factor characterizing the weakening of the magnon tunnel transmission with increasing chain length. The form of the factor ζ is similar to that which appears in the modified model of electron interelectrode tunneling [20–23]. However, the physical meaning of parameters E_c and β that defines quantity $\alpha = (E - E_c)/2\beta$ differs from those that characterize electron tunneling.

3. Results and discussion

The average magnon flux power W depends on many factors, including the parameters of the exchange interaction in the AWB system, the values of single-ion anisotropy, the external magnetic field, and also the temperatures T_A and T_B of bulk ferromagnets. In this paper, we restrict ourselves to an analysis of the magnon tunneling process from ferromagnet A to a colder ferromagnet B. The fulfillment of condition (5) suggests that the thermodynamic properties of a bulk magnet are well described in the model of non-interacting magnons, i.e., the model of an ideal Bose gas. In this model, a magnon is an excitation in which each paramagnetic unit n changes the projection of its spin with S_n to $S_n - 1$ (if H is parallel to the $0Z$ axis) or from $-S_n$ to $-(S_n - 1)$ (if H is in the antiparallel direction to the $0Z$ axis). This means that in weak magnetic fields, a jump of spin excitation between neighboring units is forbidden for an antiparallel orientation of the corresponding spins. In the situation under consideration, it is assumed that the external magnetic fields H_r and H are weak and parallel to the $0Z$ axis. The condition (5) also implies that in the model of free magnons, the ferromagnets A and B play the role of magnon baths (Fig. 2). The energy distribution of magnons in a bath is governed by the equation (4).

For a qualitative analysis, let us consider a symmetric AWB system, where

$$S_A = S_B \equiv S_r,\ S_a = S_b \equiv S_l,\ J_A = J_B,\ z_A = z_B \equiv z_r,$$
$$J_{Aa} = J_{Bb} \equiv J_{rl},\ J_{a1} = J_{bN} \equiv J_{lc},\ D_A = D_B \equiv D_r,$$
$$D_a = D_b \equiv D_l,\ g_A = g_B \simeq g_a = g_b \simeq 2.$$

In this case, the power (16) appears in the form

$$W = \frac{\beta_{rl}^4 \beta_{lc}^4}{64\pi^3 \hbar \beta_r^3} \int_{E_r}^{E_r+2\beta_r z_r} dE\,(f_A(E) - f_B(E)) \times$$
$$\times \frac{E(E-E_r)G_{1N}^2(E-E_c)}{[(E-E_l)^2 + \Gamma_l^2(E-E_r)/4]^2}. \quad (20)$$

As can be seen from a comparison of the results presented in Fig. 3a and Fig. 3b, for the selected parameters, the efficiency of magnon transfer across the paramagnetic wire simulates an exponential drop, $W \sim \exp(-N\zeta_{\text{eff}})$, which can be conditionally characterized using the effective attenuation factor ζ_{eff} (per one chain unit). This factor reflects the complex processes associated with all the tunnel pathways enclosed in the energy window

$$E_r \le E \le E_r + 2\beta_r z_r. \quad (21)$$

In this window, each tunneling pathway occurs at a tunneling energy E and is characterized by the specific attenuation factor (19). In contrast, ζ_{eff} is just an apparent attenuation factor reflecting the main integral features of the tunneling process. The latter includes the virtual (bridging) participation of spin excitations in the ferromagnetic wire.

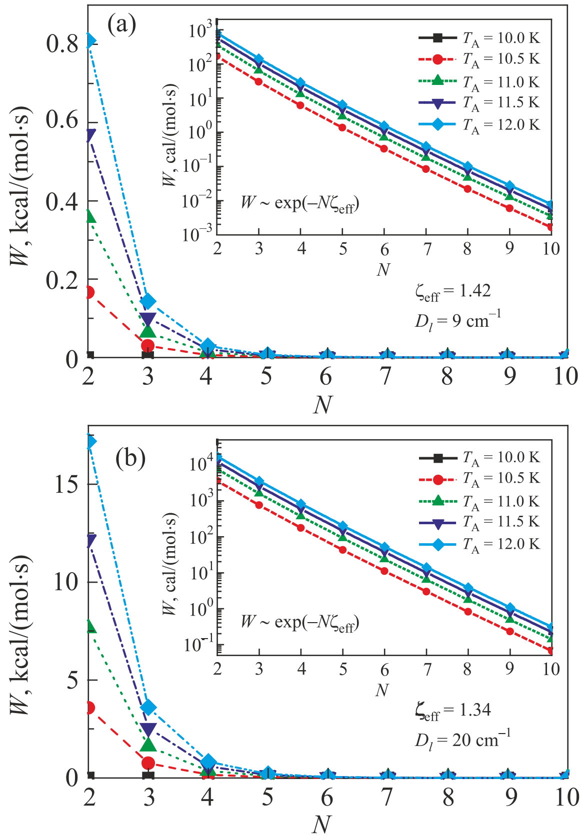

Fig. 3. Magnon tunneling between ferromagnetic dielectrics connected by a ferromagnetic wire. An exponential similar drop in the transmitted power is explained by the virtual participation of the spin excitation of the chain units while non-resonant (a) and resonant (b) tunneling of magnons through terminal wire units is controlled by changing the single-ion anisotropy D_l. The curves are calculated in using Eq. (20) with $\beta_r = 7$ cm^{-1}, $\beta_{rl} = 5$ cm^{-1}, $\beta_{lc} = 3$ cm^{-1}, $\beta = 7$ cm^{-1}, $z_r = 6$, $D_r = 30$ cm^{-1}, $D_l = 9$ cm^{-1}, $D_l = 0$ cm^{-1}, $S_r = S_l = 1$, $S = 1/2$, $g_r \simeq g_l \simeq g \approx 2$, $T_B = T = 10$ K, $T_A = T + \Delta T$.

Therefore, the efficiency of magnon tunneling strongly depends on the exchange couplings between the structural units in the AWB system (parameters β_{rl} and β_{lc}) and on how much the spin excitation energy of the terminal and internal units of the wire ($E_{a(b)}$ and E_c, respectively) differ from the lowest energies of bulk ferromagnets (E_A and E_B). So, for example, when comparing tunneling in two AWB systems, where the values of the single-ion anisotropy parameters are $D_l = 9$ cm^{-1} and $D_l = 20$ cm^{-1}, the amount of energy carried by the tunneling magnons is an order of magnitude larger through the wire where D_l is greater (compare the Fig. 3a and Fig. 3b). This is dictated by the fact that at $D_l = 20$ cm^{-1} the energy of spin excitation of the terminal unit exceeds the lowest magnon energy in the bulk ferromagnet (i.e. $E_{a(b)} > E_{A(B)}$) and, consequently, the resonant hopping, of the magnon from the ferromagnet A to the adjacent terminal unit a and from the terminal unit b to the ferromagnet B becomes possible. At the same time,

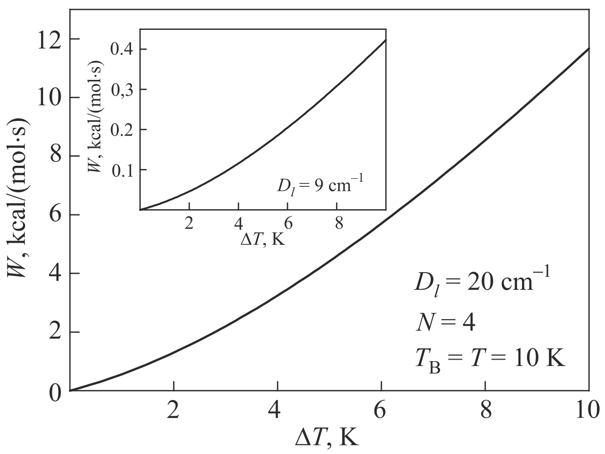

Fig. 4. Efficiency of distant tunneling energy transfer of magnons across a ferromagnetic wire at resonant and non-resonant (see inset) transmission of magnons through terminal paramagnetic wire units. The curves are calculated in using Eq. (20) with the same parameters as those for Fig. 3.

the exponentially like behavior of W is preserved. This is because the maximum value of the spin excitation in the chain, $E_c + 2JS$, is less than the minimum magnon energy $E_{A(B)}$ in a bulk ferromagnet (cf. Fig. 2). This is also reflected in the dependence of the energy transferred by magnons from ferromagnet A to ferromagnet B, depending on the temperature difference between the ferromagnets ΔT (compare the plots at $D_l = 9$ cm^{-1} and $D_l = 20$ cm^{-1} given in Fig. 4).

4. Conclusion

This work shows a possible mechanism for the distant transfer of magnon energy from one ferromagnetic dielectric to another through a low-dimensional magnetically ordered structure (ferromagnetic wire) in the presence of a temperature gradient between ferromagnets. An expression is obtained for the power of energy transferred by magnons under conditions of coherent regime of transmission. This regime is due to the tunneling of magnon through a ferromagnetic chain, which acts as a bridge structure. The efficiency of magnon tunneling substantially depends on the difference in the energies of spin excitations in bulk ferromagnets, terminal groups of a ferromagnetic wire and the inner part of the wire (the latter is the chain of exchange-coupled repeating paramagnetic units). Since these energies are characterized by exchange parameters, single-ion anisotropy, and the magnitude and direction of the magnetic field, there are many ways to control tunneling. As an example, we have shown the effect of single-ion anisotropy.

There are various ways to prepare ABC systems. In them, magnetically ordered wires can be, for example, metal-organic chains [7], a spin chain can be located on a substrate [9], and magnetic filaments are also formed in the bulk magnets [24,25]. Thus, it becomes possible to experimentally study the tunneling of magnons — one of the new processes in magnon spintronics. Note that the tunneling mechanism can also be combined with hopping mechanisms of distance transport of magnons. This means that when analyzing the forthcoming experimental results on the remote transfer of magnons through quasi-one-dimensional magnetic structures, the interpretation of the magnon transmission should be carried out taking into account both tunneling and hopping processes.

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Тунельний потік магнонів крізь обмежений феромагнітний ланцюжок

Е.Г. Петров

Запропоновано механізм перенесення магнонної енергії від одного феромагнетика до іншого шляхом тунелювання магнонів через містковий провід, що зв’язує феромагнетики. У межах моделі Бозе-газу магнонів отримано вирази для потужності енергії, яку переносять магнони від феромагнетика з вищою температурою до холоднішого феромагнетика. Показано, що ефективність тунельного транспорту магнонів залежить від параметрів обмінної взаємодії у системі «феромагнетик–провід–феромагнетик», однойонної анізотропії структурних одиниць системи, а також магнітного поля. Як приклад обговорюється роль однойонної анізотропії у формуванні резонансного та нерезонансного перенесення магнонів між феромагнетиками та термінальними одиницями дроту. Анізотропні властивості останніх здатні посилювати чи послаблювати тунельний потік магнонів між феромагнетиками.

Ключові слова: тунельний потік магнонів, феромагнітний провід, одноіонна анізотропія, парамагнітні іони.