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Scattering of Exchange Spin Waves by an Interface between Biaxial Ferromagnets with Mutual Antiferromagnetic Ordering

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The scattering of exchange spin waves caused by the interface between antiferromagnetically ordered magnetic media is studied. It is shown that, in contrast to the case of uniaxial magnets, when the scattered wave is evanescent, in this case, emission of a propagated wave is possible, the amplitude of which is determined by the difference between the biaxial anisotropy constants.

Keywords: reflection and transmission, exchange spin waves, evanescent waves, precession chirality, ferromagnets with broken axial symmetry.

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1. Introduction

Nowadays, the possibilities to use exchange spin waves (ESW) as potential carriers of information and signals have grown significantly. In addition to the low propagation speed, ESWs, as opposed to other waves, have an important feature, i.e. the direction of magnetic moment rotation (chirality) dependent on its equilibrium orientation. Hence, conditions of ESW propagation in opposite directions can be different. This fact can be taken as a basis for the functioning of logical magnonic devices at frequencies of femtosecond range — isolators, phase shifters, etc. [1], that use the nonreciprocity caused by the presence of selected direction of rotation.

It is well known that due to the quadratic law of dispersion the propagation of pure exchange waves is reciprocal in an unbounded medium. However, this condition may not be valid for magnetostatic waves [2]. At the same time, adjoining magnetic moments during ESW propagation can not have different chirality of precession tending to save their mutual orientation during rotation. This circumstance has not been taken into account in [3] when considering the ESW scattering by a plane boundary. At the same time, in [4,5] it is noted that with scattering by a plane boundary, in addition to bulk ESWs (EWs), surface waves (or evanescent waves, EVW) with an opposite bulk chirality can arise as well. Saving of the chirality at scattering is ensured by the fact that such waves necessarily arise at the boundary in pairs and scattered into different media. At the same time, the scattered waves inherit chirality of the incident wave. Therefore, it would appear reasonable that if equilibrium magnetizations in the bordering media are antiparallel, then the same chirality in them is possessed by different types of waves: EWs in one medium and EVW in another medium, which in fact means their unidirectional propagation. This is true for both scattering and generating the ESW [6]. In the latter case, chirality is defined by the uniform pumping field, which orientation can be varied, thus switching the direction of ESW propagation.

In recent studies [7,8], the problem of scattering and generating of ESWs with antiferromagnetic mutual orientation of bordering media was considered for the case of uniaxial ferromagnets (FM). In such a model, waves are generated unidirectionally, because if in one of media waves are of EW type, then in the other medium waves must be of EVW type. At the same time, with scattering a complete reflection of waves with a phase shift takes place. Therefore, in a similar problem with biaxial magnetic media effects can be expected that are related to disturbance of the axial symmetry, in particular, the simultaneous existence of EVW and EW and their emission into the bordering medium.

2. Wave types in biaxial magnetic structure

Let us consider ESW scattering by a boundary of two semi-infinite biaxial magnetic media A and B with a rigid interlayer antiferromagnetic exchange bond. We assume that ESW propagates along the normal to the boundary (z axis), while the equilibrium magnetization in layers is oriented along the x axis. Fig. 1 illustrates the geometry of the problem.

In a uniaxial FM with an antiferromagnetic bond in layer A, incident and reflected bulk ESWs are propagated,

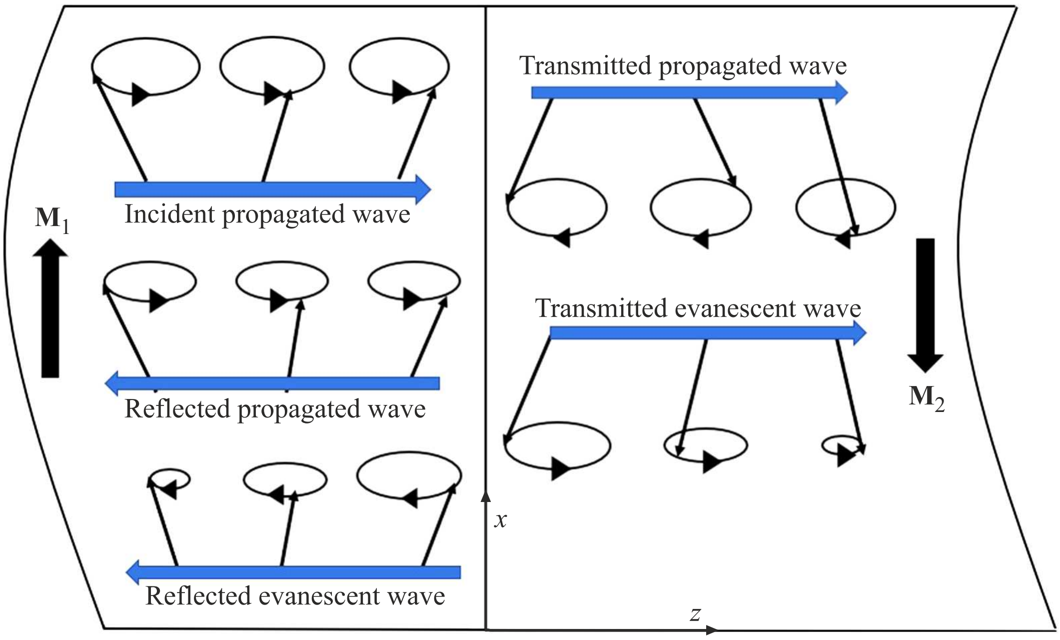

Figure 1. Geometry of the problem of scattering by an isolated boundary, wave types and their polarization.

and in layer B the transmitted evanescent wave is propagated [7], so in layer A there are no EVWs, while in layer B there are no EWs. However, in the case of disturbance of the axial symmetry the latter will have an amplitude determined by the difference between anisotropy constants along y and z directions.

When there is no attenuation and external pumping field, the dynamics of magnetization in each medium is described by the Landau–Lifshitz equation (LLE) linearized by small deviations of magnetization from the equilibrium state:

$$\dot{\mathbf{m}}_n - \gamma\left[\mathbf{M}_{0n} \times \frac{\delta w_n}{\delta m_n}\right] = 0. \quad (1)$$

The energy density of a biaxial FM quadrated by small deviations has the following form:

$$w = \frac{1}{2}\left(\lambda^2\left(\frac{dm^2}{dz}\right) + \beta_y m_y^2 + \beta_2 m_2^2\right). \quad (2)$$

By substituting it into the LLE we get the following system:

$$\begin{cases} \sigma\omega_0(\lambda^2k^2 + \beta_y)m_y + i\omega m_z = 0 \\ \sigma\omega_0(\lambda^2k^2 + \beta_z)m_z - i\omega m_y = 0 \end{cases}, \quad (3)$$

where $\omega_0 = \gamma M_0$, $\sigma = \pm 1$ — the polarization marker. By zeroing the determinant of (3), we get a dispersion equation without the σ marker:

$$\omega^2 = \omega_0^2(\lambda^2k^2 + \beta_y)(\lambda^2k^2 + \beta_z). \quad (4)$$

Let us represent solutions to system (3) in the following form

$$m_y = Ce^{i(kz-\omega t)}, \quad m_z = iDe^{i(kz-\omega t)} \quad (5)$$

and determine the ellipticity as $\eta = D/C$. Then, from system (3) we obtain

$$\eta = \sigma\,\frac{\omega_0^2(\lambda^2k^2 + \beta_y)}{\omega}. \quad (6)$$

From dispersion equation (4) follow frequency dependencies of wave numbers:

$$\lambda^2k_{p/e}^2 = \pm\sqrt{\Omega^2 + \delta\beta^2} - \beta,$$

where

$$\beta = \frac{\beta_z + \beta_y}{2}, \quad \delta\beta = \frac{\beta_z - \beta_y}{2}, \quad \Omega = \frac{\omega}{\omega_0}, \quad (7)$$

one of which is a real number (that corresponds to EW), and another is an imaginary number (EVW).

By substituting (7) into the expression for ellipticity, we get

$$\eta_{p/e} = \sigma\,\frac{\lambda^2k_{p/e}^2 + \beta - \delta\beta}{\Omega} = \sigma\,\frac{\pm\sqrt{\Omega^2 + \delta\beta^2} - \delta\beta}{\Omega}$$
$$= \pm\sigma\,\frac{\Omega}{\sqrt{\Omega^2 + \delta\beta^2} \pm \delta\beta}, \quad (8)$$

with in particular the implication of orthogonality of polarization ellipses of EW and EVW: $\eta_p\eta_e = -1$.

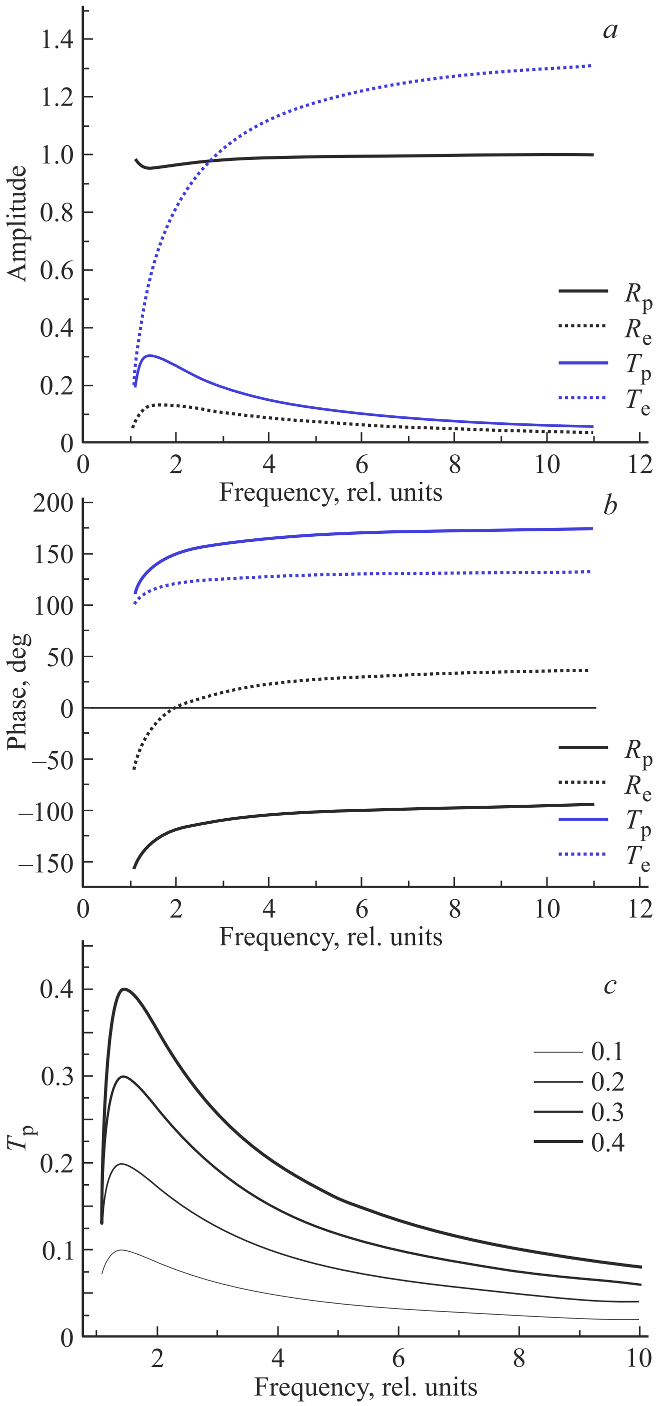

Figure 2. Frequency dependencies: *a* — reflection and transmission amplitude coefficient of EW (solid lines) and EVW (dotted lines); *b* — their phases at $\beta = 1$, $\delta\beta = 0.3$ for an isolated boundary; *c* — dependencies of the bulk wave transmission coefficient for $\delta\beta$ specified in the insert.

Thus, with $\sigma = +1$ EW is a right-hand polarized wave (with positive ellipticity), while EVW is a left-hand polarized wave. If, however, $\sigma = -1$, then the situation is the opposite: EW has a left-hand polarization and EVW has a right-hand polarization.

Let us represent the system of boundary conditions for the normalized magnetization

$$\begin{cases} \mathbf{M}_\mathrm{A} \times \mathbf{M}_\mathrm{B} = 0, \\ M_\mathrm{A} \dfrac{A_\mathrm{A}}{M_\mathrm{A}^2} \mathbf{M}_{0\mathrm{A}} \times \dfrac{d\mu_\mathrm{A}}{dz} = M_\mathrm{B} \dfrac{A_\mathrm{B}}{M_\mathrm{B}^2} \mathbf{M}_{0\mathrm{B}} \times \dfrac{d\mu_\mathrm{B}}{dz} \end{cases} \tag{9}$$

in the following form:

$$\begin{cases} \sigma_\mathrm{A}\mu_{\mathrm{B}\pm} - \sigma_\mathrm{B}\mu_{\mathrm{A}\pm} = 0 \\ \sigma_\mathrm{A} A_\mathrm{A} \dfrac{d\mu_{\mathrm{A}\pm}}{dz} - \sigma_\mathrm{B} A_\mathrm{B} \dfrac{d\mu_{\mathrm{B}\pm}}{dz} = 0 \end{cases},$$

which results in the following equations in the case when $\sigma_\mathrm{A} = +1$, $\sigma_\mathrm{B} = -1$:

$$\mu_{\mathrm{A}y/z} + \mu_{\mathrm{B}y/z} = 0,$$

$$A_\mathrm{A} \frac{d\mu_{\mathrm{A}y/z}}{dz} + A_\mathrm{B} \frac{d\mu_{\mathrm{B}y/z}}{dz} = 0. \tag{10}$$

Components of the magnetization in each medium are

$$\mu_{\mathrm{A}y} = 1 \cdot e^{ik_{\mathrm{A}p}z} + r_p e^{-ik_{\mathrm{A}p}z} + r_e e^{|k_{\mathrm{A}e}|z},$$

$$\mu_{\mathrm{A}z} = i\Big(\eta_{\mathrm{A}p}\Big(1 \cdot e^{ik_{\mathrm{A}p}z} + r_p e^{-ik_{\mathrm{A}p}z}\Big) + \eta_{\mathrm{A}e} r_e e^{|k_{\mathrm{A}e}|z}\Big),$$

$$\mu_{\mathrm{B}y} = t_p e^{ik_{\mathrm{B}p}z} + t_e e^{-|k_{\mathrm{B}e}|z},$$

$$\mu_{\mathrm{B}z} = i(\eta_{\mathrm{B}p} t_p e^{ik_{\mathrm{B}p}z} + \eta_{\mathrm{B}e} t_e e^{|k_{\mathrm{B}e}|z}). \tag{11}$$

Note, that in this case

$$\eta_{\mathrm{A}p} = \eta_\mathrm{A}, \ \ \eta_{\mathrm{A}e} = -\eta_\mathrm{A}^{-1},$$

however

$$\eta_{\mathrm{B}p} = -\eta_\mathrm{B}, \ \ \eta_{\mathrm{B}e} = +\eta_\mathrm{B}^{-1}, \tag{12}$$

where

$$\eta_n = \frac{\Omega}{\sqrt{\Omega^2 + \delta\beta_n^2} + \delta\beta_n}.$$

With consideration to (11) and (12), let us represent the system of boundary conditions as follows:

$$\begin{cases} r_p + r_e + t_p + t_e = -1, \\ \eta_\mathrm{A} r_p - \eta_\mathrm{A}^{-1} r_e - \eta_\mathrm{B} t_p + \eta_\mathrm{B}^{-1} t_e = -\eta_\mathrm{A}, \\ A_\mathrm{A}(-ik_{\mathrm{A}p} r_p + |k_\mathrm{A} e| r_e) + A_\mathrm{B}(ik_{\mathrm{B}p} t_p \\ \qquad\qquad - |k_{\mathrm{B}e}| t_e) = -iA_\mathrm{A} k_{\mathrm{A}p}, \\ A_\mathrm{A}(-ik_{\mathrm{A}p}\eta_\mathrm{A} r_p - \eta_\mathrm{A}^{-1}|k_{\mathrm{A}e}| r_e) \\ \quad + A_\mathrm{B}(-ik_{\mathrm{B}p}\eta_\mathrm{B} t_p - \eta_\mathrm{B}^{-1}|k_{\mathrm{B}e}| t_e) = -iA_\mathrm{A}\eta_\mathrm{A} k_{\mathrm{A}p}. \end{cases} \tag{13}$$

Let us consider a special case when magnetic parameters of A and B media are the same. Then subscripts of media can be omitted and the system of boundary conditions can be obtained in a matrix form:

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ \eta^2 & -1 & -\eta^2 & 1 \\ \xi & 1 & -\xi & -i \\ \xi\eta^2 & -i & \xi\eta^2 & -i \end{pmatrix} \begin{pmatrix} r_p \\ r_e \\ t_p \\ t_e \end{pmatrix} = \begin{pmatrix} -1 \\ -\eta^2 \\ \xi \\ \xi\eta^2 \end{pmatrix}, \qquad (14)$$

where

$$\xi = \frac{k_p}{|k_e|} = \sqrt{\frac{\sqrt{\Omega^2+\delta\beta^2}-\beta}{\sqrt{\Omega^2+\delta\beta^2}-\beta}},$$

$$\eta = \frac{\Omega}{\sqrt{\Omega^2+\delta\beta^2}+\delta\beta}. \qquad (15)$$

The amplitude coefficients following from system (14) can be represented as follows:

$$r_p = \frac{\eta^2(1+\xi^2)}{(\xi\eta^2+i)(\xi+i\eta^2)}, \quad r_e = \frac{\xi\eta^2(\eta^2-1)(\xi-i)}{(\xi\eta^2+i)(\xi+i\eta^2)},$$

$$t_p = \frac{i\xi(\eta^4-1)}{(\xi\eta^2+i)(\xi+i\eta^2)}, \quad t_e = -\frac{\xi\eta^2(\eta^2+1)(\xi+i)}{(\xi\eta^2+i)(\xi+i\eta^2)}. \qquad (16)$$

It can be seen from (16), that within uniaxial media, when $\eta \to 1$, for the coefficients it is true that $r_e, t_p \to 0$. This is explained by the fact that in the case of uniaxial FM with antiparallel equilibrium orientation of their magnetization, in one of the media only EWs exist, and in another medium only EVW exist. A disturbance of the magnetic axial symmetry, however, results in the situation when EWs can propagate in the medium with the opposite saturation magnetization, at the same time their amplitude is determined by the value of $\delta\beta$ (Fig. 2, *c*).

As it follows from Fig. 2, the maximum ESW transmission coefficient *n* has an order of magnitude of $\delta\beta$. It is worth to note that for the frequency where ESW polarization ellipses of the same type in the bordering media are reciprocal, the solution to system (13) is $r_e = 0$ and $t_p = 0$, similar to the case of uniaxial media. In addition, the condition of $\eta_A\eta_B = 1$ for $\delta\beta_A = -\delta\beta_B$, when ellipses of anisotropy constants are the same, but rotated by 90°, is fulfilled for all frequencies.

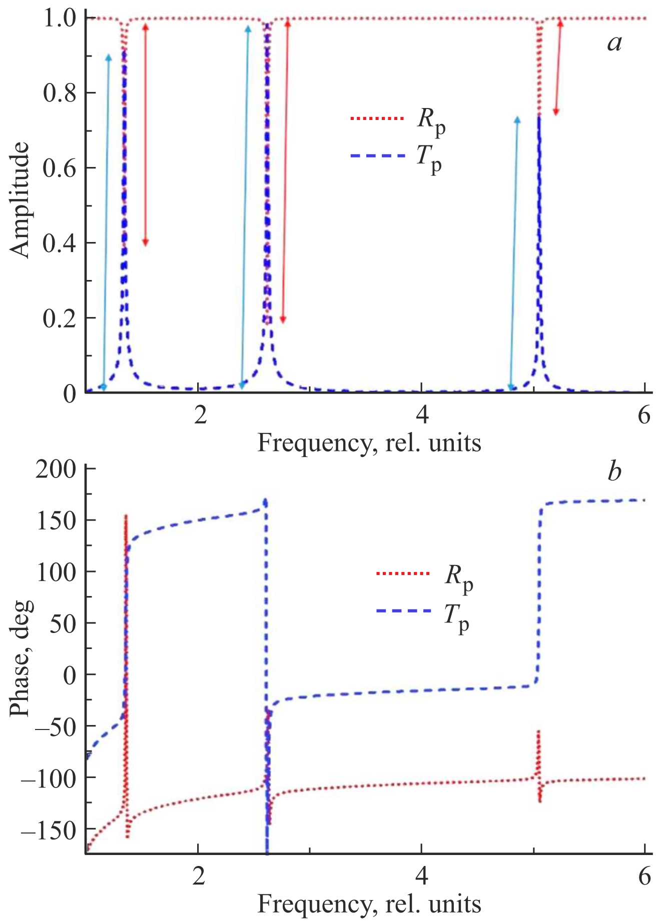

Figure 3. *a* — Absolute amplitude reflection R_p (dotted lines) and transmission T_p (dashed lines) coefficients and *b* — their phases for EW at $\beta = 1$, $\delta\beta = 0.3$ for the layer.

In the case when the ESW is scattered by an antiferromagnetically ordered (in relation to the environmental structure) layer with a thickness of *L*, the calculation results in the following system for scattering coefficients:

Corresponding dependencies (amplitudes and phases of the scattered bulk waves) are shown in Fig. 3.

As it follows from Fig. 3, profiles of reflection and transmission coefficients are different due to the influence of EVW. Maxima of the incident wave absorption corre-

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ \eta^2 & -1 & -\eta^2 & -\eta^2 & 1 & 1 & 0 & 0 \\ \xi & i & -\xi & \xi & -i & i & 0 & 0 \\ \xi\eta^2 & -i & \xi\eta^2 & -\xi\eta^2 & -i & i & 0 & 0 \\ 0 & 0 & e^{ik_pL} & e^{-ik_pL} & e^{-|k_e|L} & e^{|k_e|L} & 1 & 1 \\ 0 & 0 & -\eta^2 e^{ik_pL} & -\eta^2 e^{-ik_pL} & e^{-|k_e|L} & e^{|k_e|L} & \eta^2 & -1 \\ 0 & 0 & -\xi e^{ik_pL} & \xi e^{-ik_pL} & -ie^{-|k_e|L} & ie^{|k_e|L} & -\xi & -i \\ 0 & 0 & \xi\eta^2 e^{ik_pL} & -\xi\eta^2 e^{-ik_pL} & -ie^{-|k_e|L} & ie^{|k_e|L} & -\xi\eta^2 & i \end{pmatrix} \begin{pmatrix} r_p \\ r_e \\ A_p^{(+)} \\ A_p^{(-)} \\ A_e^{(+)} \\ A_e^{(-)} \\ t_p \\ t_e \end{pmatrix} = -\begin{pmatrix} 1 \\ \eta^2 \\ -\xi \\ -\xi\eta^2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}.$$

spond to the interferential amplification of direct and reverse waves in the layer and are observed at the frequencies where corresponding wavelength is a multiple of the film thickness.

3. Conclusion

The main feature of biaxial ferromagnets is the possibility to control the amplitude of bulk ESWs in them in the case of scattering of these waves. This is related to the simultaneous existence of both EVWs and EWs in them. The effect manifests to the extent of the difference between the anisotropy constants of axes in the plane of magnetization precession and the elliptical polarization arising due to it. Concurrently, in uniaxial ferromagnets where magnetization precession is circular, only one type of waves can exist and the scattered wave is EVW. Thus, the controllable mechanism of ESW emission is the possibility to change the axial symmetry of both the magnetic structure and the shape of the specimen, for example, due to a mechanical impact. In other respects, the properties of waves are similar to properties of uniaxial ferromagnets. In particular, this applies to frequency dependencies of the scattering coefficient [4].

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Conflict of interest

The author declares that he has no conflict of interest.

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