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Reflection and Refraction of Bulk Exchange Spin Wave on the Interface of Two Ferromagnetic Media in Planar Magnetic Field

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Strictly as per the compliance and regulations of :

Reflection and Refraction of Bulk Exchange Spin Wave on the Interface of Two Ferromagnetic Media in Planar Magnetic Field

S. Reshetnyak [α] & A. Berezhinsky [σ]

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I. Introduction

Recent advances in nanotechnologies and nanoelectronics call for the creation of new devices utilizing the characteristic features of spin waves. Under these circumstances it is of interest to use the geometrical-optics approximation to describe the behavior of spin waves propagating in a medium with an ingomogeneous distribution of magnetic parameters. This paper is devoted to application of geometrical optics formalism [1] to the description of behavior of spin waves propagating in a ferromagnetic medium with non-uniform distribution of magnetic parameters. Use of this approach enables to obtain a necessary veering of propagation of spin waves (in particular, a focusing) with the help of artificial inhomogeneities of medium's magnetic parameters of the given configuration, and also by change of value of an external magnetic field.

II. Equations of Magnetization Dynamics

Let us consider an infinite ferromagnet consisting of two semi-infinite homogeneous parts that are in contact along the xOz plane. In the corresponding half-spaces, these parts of ferromagnet are characterized by the saturation magnetizations M_{01} and M_{02}, exchange interaction parameters α_1 and α_2, uniaxial magnetic anisotropy β_1 and β_2, as well as by rhombic magnetic anisotropy ρ_1 and ρ_2. The easy magnetization axis of each magnet is directed along the z axis.

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The material is placed in an external uniform permanent magnetic field H_0, directed along the hard axis and the y axis of the coordinate system. Also plain $z = 0$ separates given structure from vacuum.

The energy density of such magnetic structure in exchange mode looks like

$$w=\sum_{j=1}^{2}\theta[(-1)^j y]w_j + A\delta(x)\mathbf{M}_1\mathbf{M}_2 \tag{1}$$

where

$$w_j = \frac{\alpha_j}{2}\frac{\partial m_j}{\partial x_k}\frac{\partial m_j}{\partial x_k} - \frac{\beta_j}{2} m_{jz}^2 - \rho_2\left(m_{jx}^2+m_{jz}^2\right) - H_0 M_{jy}, \tag{2}$$

$\theta(x)$ is step function; $\mathbf{M}_j = M_{0j}\mathbf{m}_j$, $\mathbf{m}_j$ are unit vectors in the direction of magnetization, j=1,2; A is the constant describing a coupling on interface between half-spaces at y=0. Note that the case A=0 is equivalent to the absence of a coupling between layers through an interface, and $A \to \infty$ corresponds to an ideal (in a coupling sense) boundary [2].

Following [3] we represent the distribution of the magnetization in the material in the form

$$\mathbf{M}_j(\mathbf{r},t) = M_{0j}\,\psi_j^+(\mathbf{r},t)\,\boldsymbol{\sigma}\psi_j(\mathbf{r},t), \tag{3}$$

where ψ_j denotes quasiclassical wave functions, which play the role of the order parameter of spin density, $\mathbf{r}$ is the radius vector in the Cartesian coordinate system, t is the time, and $\boldsymbol{\sigma}$ is a vector of Pauli matrices.
The Lagrange equations have the form

$$i\hbar\frac{\partial\psi_j(\mathbf{r},t)}{\partial t} = -\mu_0\mathbf{H}_{ej}(\mathbf{r},t)\boldsymbol{\sigma}\psi_j(\mathbf{r},t), \tag{4}$$

where μ_0 is a Bohr magneton, ħ is the Plank constant,

and $\mathbf{H}_{ej} = -\dfrac{\partial w_j}{\partial \mathbf{M}_j} + \dfrac{\partial}{\partial x_k}\dfrac{\partial w_j}{\partial\left(\partial \mathbf{M}_j/\partial x_k\right)}$.

Then, using linear perturbation theory, the solution of Eq.(4) can be written as following

$$\Psi(\mathbf{r},t) = e^{i\eta t}\begin{pmatrix}1\\ i\end{pmatrix} + Ae^{i\eta t}\begin{pmatrix}\xi(\mathbf{r},t)\\ \chi(\mathbf{r},t)\end{pmatrix}, \tag{5}$$

where $\eta = \frac{\mu_0 H_0}{\hbar}$, and where $\xi(\mathbf{r},t)$, $\chi(\mathbf{r},t)$ are small additions characterizing the deviation of magnetization from the ground state.

Linearizing Eq.(4) and taking into account Eq.(2), we obtain

$$\xi = i\chi, \tag{6}$$

$$-\frac{\hbar^2}{(2\mu_0 M_{0j})^2}\frac{\partial^2 \xi_j(\mathbf{r},t)}{\partial t^2} = \left[\alpha_j^2\Delta^2 + 2\alpha_j\left(\tilde{H}_{0j} - \beta_j/2 - \rho_j\right)\Delta + \left(\tilde{H}_{0j} - \rho_j\right)\left(-\tilde{H}_{0j} + \beta_j + \rho_j\right)\right]\xi_j(\mathbf{r},t), \tag{7}$$

where $\tilde{H}_{0j} = \frac{H_0}{M_{0j}}$.

Equation (7) describes the magnetization dynamics in the short-wavelength (exchange) approximation.

Using the approach [4] of geometrical optics, we obtain the refractive index of spin wave

$$n^{\pm} = \sqrt{\frac{\alpha_1}{\alpha_2}\frac{\beta_2/2 + \rho_2 - \tilde{H}_{02} \pm \sqrt{\Omega_2^2 + \beta_2^2/4}}{\beta_1/2 + \rho_1 - \tilde{H}_{01} \pm \sqrt{\Omega_1^2 + \beta_1^2/4}}}, \tag{8}$$

where $\Omega_j = \frac{\omega\hbar}{2\mu_0 M_{0j}}$.

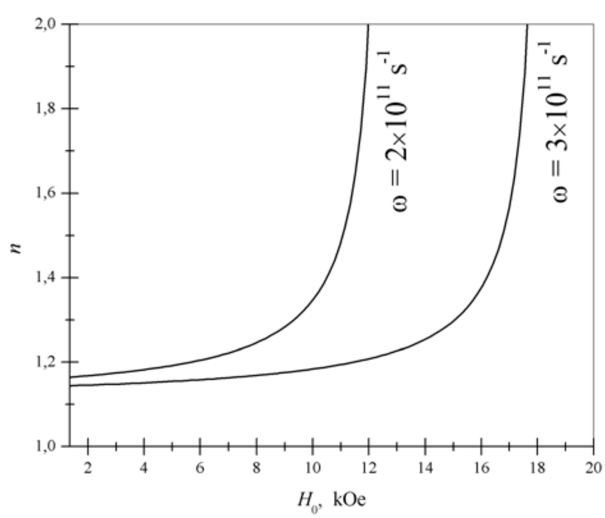

Fig.1 : Dependencies of refraction index of spin wave n on value of external homogeneous magnetic field H_0., $\alpha_1 = 7.4\times10^{-11}$ cm^2, $\alpha_2 = 5\times10^{-11}$ cm^2, $\beta_1 = 20$, $\beta_2 = 30$, $\rho_1 = 3$, $\rho_2 = 6$, $M_{01} = 90$ G, $M_{02} = 110$ G

Fig.1 shows dependency of refractive index on external magnetic field. As it can be seen from the figure it is possible to change refractive index of spin wave in a wide range of values by only changing of external magnetic field keeping constant the frequency and magnetic parameters of structure.

III. Reflection and Transmission Amplitudes

Let a spin wave to impinge on the interface from the homogeneous magnet with the parameter α_1 in the positive direction of y at an arbitrary angle.

Let's use boundary conditions for $\xi(\mathbf{r},t)$, which follow from (1)-(2):

$$\left[A\gamma(\xi_2 - \xi_1) + \alpha_1\xi_1'\right]_{y=0} = 0$$
$$\left[A(\xi_1 - \xi_2) - \gamma\alpha_2\xi_2'\right]_{y=0} = 0. \tag{9}$$

Here $\gamma = M_{02}/M_{01}$. We shall obtain the expressions for amplitudes of spin wave reflection and transmission. Suppose, incident, reflected and transmitted waves are given by $\xi_I = \exp\left(i(\mathbf{k}_0\mathbf{r} - \omega t)\right)$, $\xi_R = R\exp\left(i(\mathbf{k}_1\mathbf{r} - \omega t)\right)$ and $\xi_D = D\exp\left(i(\mathbf{k}_2\mathbf{r} - \omega t)\right)$ correspondingly. Here R is a complex reflection amplitude, D is a transmission amplitude, $\mathbf{k}_0$, $\mathbf{k}_1$ are wave vectors of incident and reflected waves correspondingly, $\mathbf{k}_2$ is a wave vector of transmitted wave. Then

$$R = \frac{k_0\alpha_1\cos\theta_1 B - iA(\alpha_1\cos\theta_1 - \gamma B)}{k_0\alpha_1\cos\theta_1 B - iA(\alpha_1\cos\theta_1 + \gamma B)},$$
$$D = \frac{-2iA\alpha_1\cos\theta_1}{k_0\alpha_1\cos\theta_1 B - iA(\alpha_1\cos\theta_1 + \gamma B)}, \tag{10}$$

where $B = \alpha_2\gamma\sqrt{n^2 - \sin^2\theta_1}$. The "±" sign next to n is neglected for simplicity.

In the case of an ideal boundary ($A \to \infty$) Eqs. (10) can be rewritten as

$$R = \frac{\alpha_1\cos\theta_1 - \alpha_2\gamma^2\sqrt{n^2 - \sin^2\theta_1}}{\alpha_1\cos\theta_1 + \alpha_2\gamma^2\sqrt{n^2 - \sin^2\theta_1}},$$
$$D = \frac{2\alpha_1\cos\theta_1}{\alpha_1\cos\theta_1 + \alpha_2\gamma^2\sqrt{n^2 - \sin^2\theta_1}}, \tag{11}$$

IV. Estimations for The Parameters of Spin-Wave Lenses

Let's give the estimations for material's parameters when a lens is thin. Obviously, we have to provide a necessary lens transparency.

Let's consider that exchange parameters A_1 and A_2 ($A_j = \alpha_j M^2/2$ [3]) are equal for both half-spaces. In this case $\alpha_1 = \alpha_2\gamma^2$ and Eqs. (11) can be reduced to

$$R = \frac{\cos\theta_1 - \sqrt{n^2 - \sin^2\theta_1}}{\cos\theta_1 + \sqrt{n^2 - \sin^2\theta_1}},$$
$$D = \frac{2\cos\theta_1}{\cos\theta_1 + \sqrt{n^2 - \sin^2\theta_1}}. \qquad (12)$$

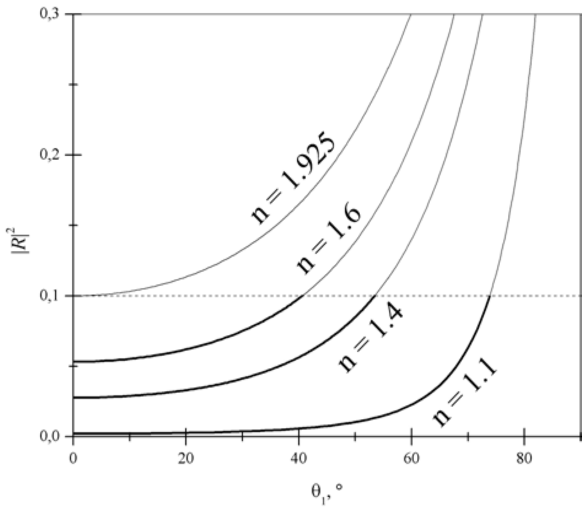

Fig.2A : Dependencies of intensity of reflected wave $|R|^2$ on the incident angle θ_1 for $1<n<2$

In Fig.2A and Fig.2B we show the dependencies of intensity of reflected wave $|R|^2$ on the incident angle θ_1 for different values of refractive index n. It can be seen that intensity depends strongly on the incident angle and intensity has the lowest values at small angles.

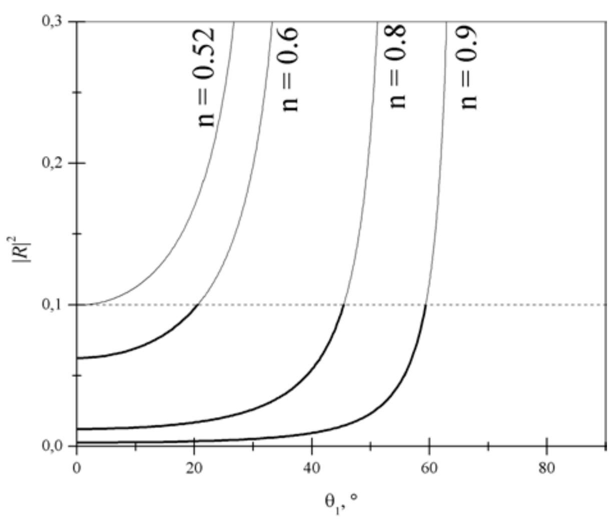

Fig.2B : Dependencies of intensity of reflected wave $|R|^2$ on the incident angle θ_1 for $0.5<n<1$

In case of small incident angles Eq. (11) can be rewritten as

$$R = \frac{\alpha_1 - \alpha_2\gamma^2 n}{\alpha_1 + \alpha_2\gamma^2 n},$$
$$D = \frac{2\alpha_1}{\alpha_1 + \alpha_2\gamma^2 n}. \qquad (13)$$

Demanding a conformity to the condition $|R|^2 < \eta$, where η is a necessary smallness of reflection coefficient, to provide enough transparency of lens, we obtain a limitation on n and, therefore, on α, β, ρ, ω, M_0 and H_0:

$$\frac{1-\sqrt{\eta}}{1+\sqrt{\eta}} < \frac{\alpha_2\gamma^2}{\alpha_1} n < \frac{1+\sqrt{\eta}}{1-\sqrt{\eta}} \qquad (14)$$

In particular, in case of $\alpha_1 = \alpha_2\gamma^2$ reflection coefficient is less then 10% if $0.52<n<1.92$.

By adjusting the relation $\alpha_2\gamma^2/\alpha_1$ one can set up the lens for working with particular refraction index. Indeed, using Eq. (13) we obtain

$$\frac{\alpha_2\gamma^2}{\alpha_1} \to \frac{1}{n}, \text{ when } \theta_1 \to 0 \text{ and } |R|^2 \to 0. \qquad (15)$$

For example, if one is going to use values of refractive index that are close to $n \approx 2$, then he should choose relation $\alpha_2\gamma^2/\alpha_1$ to be close to 0.5. In this case reflection coefficient is less then 10% if $1.04<n<3.85$ (Fig. 3).

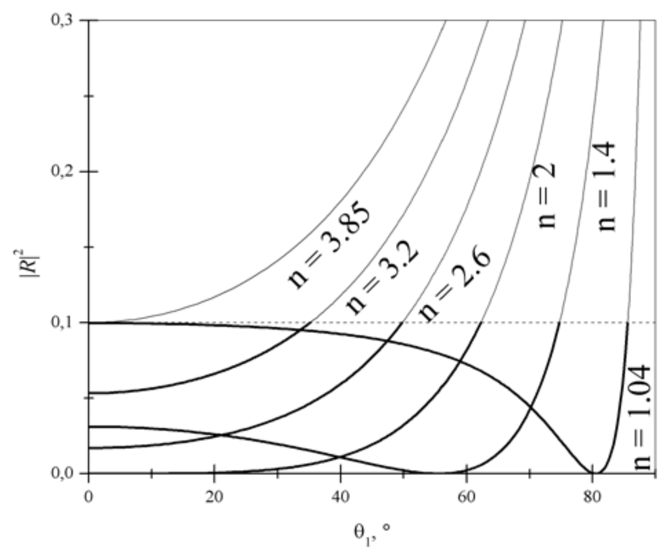

Fig.3 : Dependencies of intensity of reflected wave $|R|^2$ on the incident angle θ_1 for $1.04<n<3.85$

V. Conclusion

We have shown that it is possible to change "optical" parameters of spin-wave lens in a wide range of values by only changing of the external magnetic field keeping constant the frequency and magnetic parameters of structure. This fact allows one to use the results of this research in applications of spin-wave electronics.

It is also shown that despite the strong dependence of reflection coefficient on incident angle it is possible to obtain suitable reflection coefficient by adjusting magnetic parameters of the structure.

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