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Negative refraction of dipole-exchange spin waves through a magnetic twin interface in restricted geometry

Sang-Koog Kim,[a)] Sangkook Choi, Ki-Suk Lee, Dong-Soo Han, Dae-Eun Jung, and Youn-Seok Choi
Research Center for Spin Dynamics & Spin-Wave Devices, Seoul National University, and Nanospinics Laboratory, Department of Materials Science and Engineering, College of Engineering, Seoul National University, Seoul 151-744, Republic of Korea

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A phenomenon of negative refraction of dipole-exchange spin waves (DESWs) was demonstrated by micromagnetic modeling, based on the fact that the DESWs' dispersion is anisotropic according to the relative orientation of the DESW propagation direction with respect to the orientation of local static magnetizations. Using this anisotropic dispersion behavior, the negative refraction of the DESWs was reproduced through a magnetic twin interface in a geometrically restricted medium of cubic in-plane anisotropy. This work verifies that the negative refraction of electromagnetic waves can also occur for DESWs propagating in restricted geometry through a specially designed magnetic interface. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2936294]

In recent years, negative refraction[1,2] of electromagnetic waves ranging from microwave[3,4] to infrared[5] and even to visible frequencies[6] has become a hot research issue, owing to the facts that this phenomenon has not been achieved in naturally existing materials[2] but has been realized with artificially made metamaterials,[3,5] photonic crystals,[4] or ultrathin planar waveguides.[6] The negative refraction of electromagnetic waves has become more interesting due to its practical applications to the realization of a superlens or superprism, either of which could be used to achieve subwavelength focusing with resolution beyond the diffraction limit, or optical nanodevices such as beam steerer and modulator.[3,7]

Meanwhile, wavelike phenomena of dipole-exchange spin waves (DESWs) in a different physical system, e.g., ordered magnetic materials of restricted geometry have been explored to pursue their fundamental understanding as well as advanced technological applications.[8] The DESWs are, in principle, low-lying collective excitations of magnetizations (**M**s) in submicronsize magnetic elements, where both long-range dipolar and short-range exchange interactions between individual **M**s are primarily considered. The potential uses of DESWs as signals in new-paradigm logic devices[9,10] require the ability to steer the path of DESW rays propagating in magnetic thin-film media without the loss of high-energy flux.[11] Analogously to the case of electromagnetic waves, DESWs are also expected to be negatively refracted under peculiar conditions, based on the anisotropic dispersion relation that the magnitude of the wave vector **k** of the DESWs' propagation varies with its direction with respect to the orientation of the local static **M**. In fact, such anomalous refraction of spin waves was investigated for only magnetostatic spin waves of wavelengths ranging from 10 μm to 2 mm through a boundary between ferrite and ferrite-insulator-metal media,[12] where exchange interactions were ignored. However, for the case of DESWs of wavelengths shorter than 1 μm and high frequencies larger than 10 GHz, traveling in magnetic waveguides of the nanometer length scale, such behaviors have not been studied. In this letter, we report on an intriguing phenomenon of electromagnetic-wave-like negative refraction of DESWs, as studied by numerical micromagnetic simulations. In order to demonstrate the negative refraction of DESWs propagating in nanoscale media, we have designed a specific model interface of magnetic twin structure in a medium of geometrically restricted thin film of cubic in-plane anisotropy.

In the present modeling study, we chose a micromagnetic simulation approach[13] based on the Landau–Lifshitz–Gilbert (LLG) equation,[14] an approach that is one of the most optimized tools to elucidate electromagnetic-wave-like properties of DESWs reflected at and refracted through a magnetic interface between two dissimilar magnetic media. An advantage of this simulation approach is that one can obtain realistic **M** dynamics of sufficient temporal ($\sim$1 ps) and spatial ($\sim$1 nm) resolutions, whereas experimental measurements are often impossible due to the relatively poor resolutions of the probing techniques. The governing LLG equation is given by $\partial\mathbf{M}/\partial t=-\gamma(\mathbf{M}\times\mathbf{H}_{\text{eff}})+\alpha/|\mathbf{M}|(\mathbf{M}\times\partial\mathbf{M}/\partial t)$, with the phenomenological damping constant α and the gyromagnetic ratio γ, where the **M** precesses under an effective torque $(\mathbf{M}\times\mathbf{H}_{\text{eff}})$ attributed to $\mathbf{H}_{\text{eff}}$ that is contributed from the exchange, magnetic dipolar, and magnetic anisotropy interactions between the individual **M**s and the Zeeman interaction. Moreover, recent advanced computer capability allows for the micromagnetic simulation approach to provide quantitative information on the rich electromagnetic-wave-like properties of DESWs.

Before going further, let us re-examine the basic law of reflection and refraction with monochromatic electromagnetic waves of frequency f incident on an interface between optically different media, not only in the real (x-y) plane but also in the wavevector (k_x-k_y) plane, as illustrated in Figs. 1(a) and 1(b), respectively.[15] When plane waves of wave vector $\mathbf{k}^0$ and group velocity $\mathbf{v}_g^0$ are incident on an interface, some of them return to (are reflected into) medium 1 with $\mathbf{k}'$ and $\mathbf{v}_g'$, and the rest of them pass through the interface (are refracted) and continue to propagate in medium 2 with $\mathbf{k}''$ and $\mathbf{v}_g''$, where $\mathbf{v}_g\equiv\nabla_{\mathbf{k}}f^{\text{medium}}(\mathbf{k})$. The optical rule governing

a)Author to whom correspondence should be addressed. Electronic mail: sangkoog@snu.ac.kr.

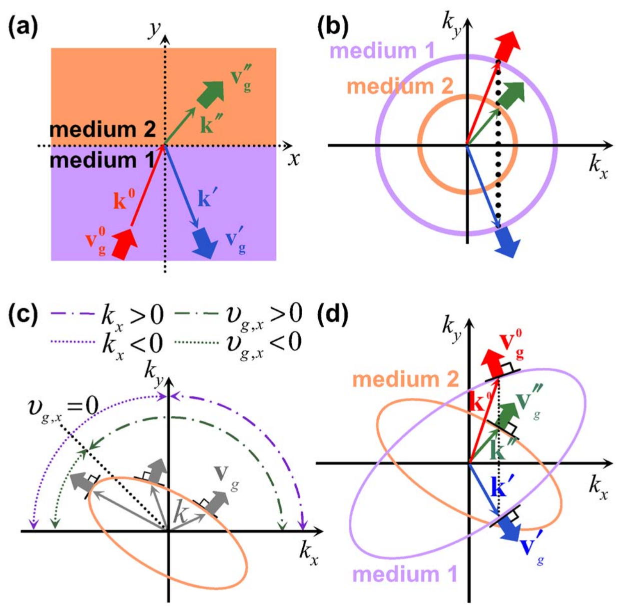

FIG. 1. (Color online) Schematic illustrations of reflection and refraction of electromagnetic waves at an interface between optically different media, but each is isotropic, in the real (x-y) plane and wave vector (k_x-k_y) plane, as shown in (a) and (b), respectively. The purple and apricot circles on the (k_x-k_y) plane indicate the individual frequency contours of the allowed modes in the same-color-coded media 1 and 2, respectively. The color-coded thin and thick arrows denote the $\mathbf{k}$ and $\mathbf{v}_g$ of the electromagnetic waves propagating in each medium, as indicated by the incident (red), reflected (blue), and refracted (green) rays. (c) The frequency contour of the allowed mode in an anisotropic medium. The thin and thick gray arrows denote examples of the allowed $\mathbf{k}$ and $\mathbf{v}_g$ in the medium, respectively. (d) Schematic diagram illustrating an example of negative refraction of electromagnetic waves through an interface between anisotropic media 1 and 2.

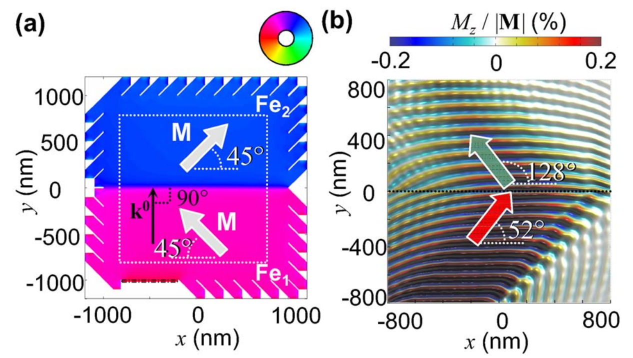

FIG. 2. (Color online) (a) The model system employed, made of 5-nm-thick Fe film, for the demonstration of DESWs' negative refraction. (b) Plane-view, snapshot image of the spatial distribution of the local $M_z/|\mathbf{M}|$, taken at t=4 ns. The thick arrows indicate the directions of the group velocity vectors of the propagating DESWs in each medium.

relations between the incident, reflected, and refracted waves is Snell's law that satisfies the continuity of the tangential components of the $\mathbf{k}$ vector across the interface (along the x axis), such that $k_x^0 = k_x' = k_x''$ [vertical dotted line in Fig. 1(b)]. The wave propagation inside each medium is determined by the dispersion relation of each medium. In Fig. 1(b), the constant frequency contours of the allowed modes in the different media are plotted on the (k_x-k_y) plane, and are circular in shape in the case of optically isotropic media. Each propagation direction is normal to the corresponding frequency dispersion contour surface at the condition $k_x^0 = k_x' = k_x''$; thereby, the energy flow of electromagnetic waves propagates along the allowed $\mathbf{k}$ vectors in the given isotropic media, as displayed in Fig. 1(b); that is, the directions of $\mathbf{k}$ and $\mathbf{v}_g$ for any incident, reflected, or refracted waves are always parallel to each other.

In contrast, in a certain medium of optical anisotropy, the frequency contours of the allowed modes are anisotropic [Fig. 1(c)]. Correspondingly, it is not necessary that $\mathbf{v}_g$ be parallel to $\mathbf{k}$ according to the direction of $\mathbf{k}$. In some cases, the direction of $\mathbf{v}_g$ (thick gray arrows) can differ from that of $\mathbf{k}$ (thin gray arrows), as illustrated in Fig. 1(c). Consequently, $v_{g,x}$ and k_x in an anisotropic medium can have either the same or the opposite sign, according to the direction of $\mathbf{k}$ relative to the optical axis of the medium, as shown in Fig. 1(c), where $v_{g,x(y)} = \mathbf{v}_g \cdot \hat{\mathbf{e}}_{x(y)}$ with the unit vector $\hat{\mathbf{e}}_{x(y)}$ along the (x) y axis. For the case of an interface between optically anisotropic dissimilar media, when $v_{g,x}$ and k_x have the opposite sign in medium 1 and the same sign in medium 2, the sign of $v''_{g,x}$ should be opposite to that of $v^0_{g,x}$ for the condition $k_x^0 = k_x' = k_x''$, which is required for the negative refraction possible, as visualized in Fig. 1(d). Such a condition would be possible either at an interface between a normal right-handed material and a left-handed material of negative permittivity and permeability[1,2] or at a special interface of twining structure in uniaxial crystals, where the interface is a reflection symmetry plane.[16]

Analogously to the case of electromagnetic waves as described above, DESWs are also expected to be negatively refracted under peculiar conditions, based on their anisotropic dispersion relation. In order to demonstrate the negative refraction of DESWs, we designed a special model interface of magnetic twin structure because it could be readily obtained from real samples such as cubic in-plane anisotropy material.[17] The model system used for our numerical simulation was composed of 5- nm-thick Fe film of cubic magnetic anisotropy.[18] The cubic anisotropy allows the static $\mathbf{M}$ orientation to saturate along the direction $(x,y,z) = (-1,1,0)$ in the Fe_1 region ($y < 0$ nm) and along the direction $(x,y,z) = (1,1,0)$ in the Fe_2 region ($y > 0$ nm), as displayed in Fig. 2(a), resulting in a magnetic twin interface with a 90° domain wall (along the x axis). The thorny shape at the edges of such a finite-size model system was designed to align the local $\mathbf{M}$s near the edge boundaries along the desired $\mathbf{M}$ orientations in both the Fe_1 and Fe_2 media, by minimizing the influence of dipolar interactions between the magnetic free poles at the edges.[19] To excite monochromatic DESWs of f=25 GHz, incident on the magnetic twin interface with flat wavefronts parallel to the Fe_1/Fe_2 interface (the $\mathbf{k}$ vector is normal to the interface), we applied an oscillating field $H_{\text{osc}} = 250(1 - \cos 2\pi\nu_H t)$ Oe with a frequency ν_H=25 GHz only in the dash-dot boxed area in the Fe_1 region along the direction $(x,y,z) = (1,1,0)$ perpendicular to the static $\mathbf{M}$ direction $(x,y,z) = (-1,1,0)$. A snapshot image of the resultant dynamic evolution of the $M_z/|\mathbf{M}|$ distribution for the indicated area by the gray dotted box in Fig. 2(a), taken at t=4.0 ns after applying the H_{osc} is shown in Fig. 2(b). This image clearly reveals that the DESW packets with the wavefronts parallel to the Fe_1/Fe_2 interface propagated along a direction 52° from the +x direction in the Fe_1 and 128° in the Fe_2. This clearly exhibits not only that the direction of $\mathbf{v}_g$ differs from the $\mathbf{k}$ direction for both incident and refracted DESW rays, but also that $v''_{g,x}$ and $v^0_{g,x}$ have the opposite sign. This DESWs propagation behavior is similar to the negative refraction of electromagnetic waves.[2]

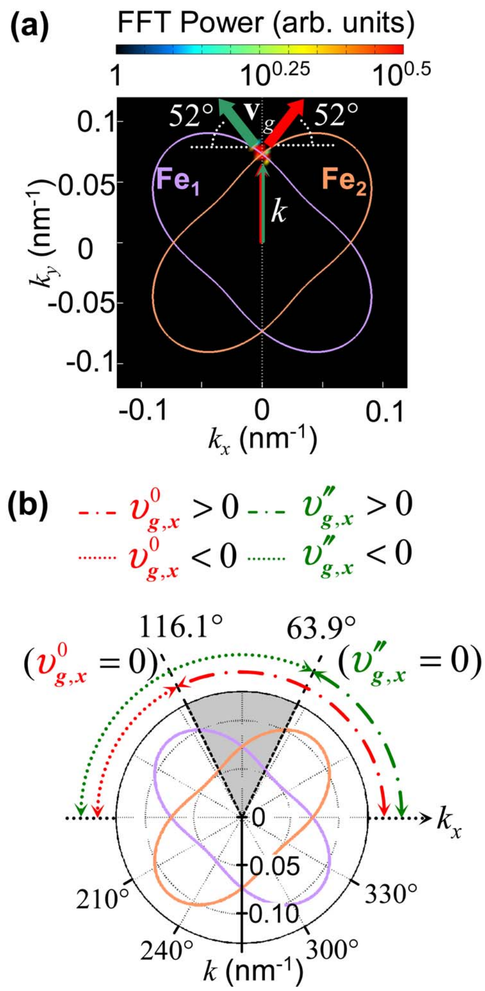

FIG. 3. (Color online) (a) The FFT power-spectrum distribution of the local $M_z/|\mathbf{M}|$ on the (k_x-k_y) plane, which are overlapped with the frequency contours of the allowed DESW mode of $f=25$ GHz in the indicated Fe_1 and Fe_2 media. The wide arrows indicate the directions of the group velocities in the corresponding media. (b) The same frequency contours in (a) are represented in the polar coordinate system. The anticipated range of the incidence angles of the **k** vector is indicated by the gray region, in which the DESWs' negative refraction takes place.

For further quantitative analysis, we made a fast Fourier transform (FFT) of the dynamic evolution of the local $M_z/|\mathbf{M}|$ distributions to obtain their power spectrum, as shown in Fig. 3(a). On the (k_x-k_y) plane, there was only one strong peak at $(k_x,k_y)=(0,0.07\ \text{nm}^{-1})$. In the FFT power distribution, the directions of $\mathbf{v}_g$ for both the incident and refracted DESWs could be identified by overlapping the anisotropic frequency contours of $f=25$ GHz in both the Fe_1 (purple) and Fe_2 (apricot) media.[20] At the $(k_x,k_y)=(0,0.07\ \text{nm}^{-1})$ peak, the directions of $\mathbf{v}_g$ for the incident and refracted DESW rays were determined to be 52° in the Fe_1 and 128° in the Fe_2 media, respectively, from the $+x$ direction, as determined by the definition of $\mathbf{v}_g \equiv \nabla_{\mathbf{k}} f^{\text{Fe}}(\mathbf{k})$ [Fig. 3(a)]. These angles are in quite good agreement with the directions of the DESW packets represented by the image of the M_z/M_s distribution, shown in Fig. 2(b). Also, the range of the incidence angle of the **k** vector, where negative refraction can occur for DESWs, were predicted from the constant frequency contours of the DESWs shown in Fig. 3(b). By the definition of $\mathbf{v}_g \equiv \nabla_{\mathbf{k}} f^{\text{Fe}}(\mathbf{k})$, the angles required for $\upsilon^0_{g,x}=0$ and $\upsilon''_{g,x}=0$ were determined to be 116.1° and 63.9° from the $+x$ direction, respectively. Between these two angles, the directions of $\upsilon^0_{g,x}$ and $\upsilon''_{g,x}$ lie opposite to each other, so that negative refraction of DESWs can take place in the range of the direction of the **k** vector from 63.9° to 116.1°. The 90° incidence angle of the **k** vector for the present simulation is just one of the probable angles for the occurrence of DESWs' negative refraction.

In conclusion, we demonstrated, by micromagnetic simulations, that negative refraction of electromagnetic waves is also a possible phenomenon for exchange-dipolar spin waves based on their anisotropic dispersion behavior, that is, that the magnitude of the spin wave propagation wave vector varies according to its direction relative to the local **M**s. The demonstrated result provides a basic mechanism by which spin waves can be guided in waveguide media of restricted geometry.

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