University of Wollongong

Research Online

Australian Institute for Innovative Materials -
Papers

Australian Institute for Innovative Materials

1-1-2020

Snell's law for spin waves at a 90° magnetic domain wall

Tomosato Hioki

Rei Tsuboi

Tom H. Johansen

University of Wollongong, tomjo@uow.edu.au

Yusuke Hashimoto

Eiji Saitoh

Follow this and additional works at: <https://ro.uow.edu.au/aiimpapers>

Part of the [Engineering Commons](#), and the [Physical Sciences and Mathematics Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Snell's law for spin waves at a 90° magnetic domain wall

Abstract

© 2020 Author(s). We report the experimental observation of the refraction and reflection of propagating magnetostatic spin waves crossing a 90° domain wall (DW). Time-resolved magneto-optical imaging was used to observe the propagation dynamics of magnetostatic spin waves. Due to the magnetization rotation across such a DW, the dispersion relation of magnetostatic spin waves rotates by 90°. This results in a change in the propagation dynamics of spin waves on both sides of the DW. We observed the refraction and reflection of magnetostatic spin waves at the DW and reveal their characteristics that include negative refraction. The incident-angle dependence of the refraction angle is explained by the wavenumber conservation along the DW, quite similar to the case of Snell's law for light.

Disciplines

Engineering | Physical Sciences and Mathematics

Publication Details

Hioki, T., Tsuboi, R., Johansen, T. H., Hashimoto, Y. & Saitoh, E. (2020). Snell's law for spin waves at a 90° magnetic domain wall. *Applied Physics Letters*, 116 (11),

Snell's law for spin waves at a 90° magnetic domain wall

Cite as: Appl. Phys. Lett. **116**, 112402 (2020); <https://doi.org/10.1063/1.5141864>

Submitted: 08 December 2019 . Accepted: 23 February 2020 . Published Online: 20 March 2020

Tomosato Hioki , Rei Tsuboi, Tom H. Johansen, Yusuke Hashimoto , and Eiji Saitoh

View Online

Export Citation

CrossMark

ARTICLES YOU MAY BE INTERESTED IN

Spintronics with compensated ferrimagnets

Applied Physics Letters **116**, 110501 (2020); <https://doi.org/10.1063/1.5144076>

Ultrafast magnetism: The magneto-optical Kerr effect and conduction electrons

Applied Physics Letters **116**, 112404 (2020); <https://doi.org/10.1063/1.5143115>

Magnetization switching induced by magnetic field and electric current in perpendicular TbIG/Pt bilayers

Applied Physics Letters **116**, 112401 (2020); <https://doi.org/10.1063/1.5140530>

Lock-in Amplifiers
Find out more today

Zurich Instruments

Snell's law for spin waves at a 90° magnetic domain wall

Cite as: Appl. Phys. Lett. **116**, 112402 (2020); doi: [10.1063/1.5141864](https://doi.org/10.1063/1.5141864)

Submitted: 8 December 2019 · Accepted: 23 February 2020 ·

Published Online: 20 March 2020

View Online

Export Citation

CrossMark

Tomosato Hioki,^{1,a)} Rei Tsuboi,¹ Tom H. Johansen,^{2,3} Yusuke Hashimoto,⁴ and Eiji Saitoh^{1,4,5}

AFFILIATIONS

¹Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

²Department of Physics, University of Oslo, 0316 Oslo, Norway

³Institute for Superconducting and Electronic Materials, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia

⁴Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

⁵Department of Applied Physics, Faculty of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

^{a)} Author to whom correspondence should be addressed: hioki.kinken@imr.tohoku.ac.jp

ABSTRACT

We report the experimental observation of the refraction and reflection of propagating magnetostatic spin waves crossing a 90° domain wall (DW). Time-resolved magneto-optical imaging was used to observe the propagation dynamics of magnetostatic spin waves. Due to the magnetization rotation across such a DW, the dispersion relation of magnetostatic spin waves rotates by 90°. This results in a change in the propagation dynamics of spin waves on both sides of the DW. We observed the refraction and reflection of magnetostatic spin waves at the DW and reveal their characteristics that include negative refraction. The incident-angle dependence of the refraction angle is explained by the wavenumber conservation along the DW, quite similar to the case of Snell's law for light.

Published under license by AIP Publishing. <https://doi.org/10.1063/1.5141864>

The relation of the angles between incident and refracted electromagnetic waves is called Snell's law. In the field of magnonics, where the propagation of spin waves plays a main role in data processing and information transfer, the reflection and refraction of spin waves are important because they enable manipulation of their phase and propagation direction.^{1–11} Refraction occurs due to a difference in the phase velocity in the two different media and is characterized by a dispersion relation. Spin waves in the small wavenumber regime (magnetostatic spin waves) have an anisotropic dispersion relation due to the anisotropic nature of the magnetic dipole interaction. Therefore, the phase velocity of magnetostatic waves depends on the angle θ_k between the magnetization $\mathbf{M}$ and the wavevector $\mathbf{k}$.

In recent years, the interplay between a magnetic domain wall (DW) and spin waves has been investigated and expanded the use of a DW for various applications in magnonics, e.g., serving a channel for spin waves or forming periodic magnetic boundaries for magnonic crystals.^{12–17} The width of a DW, typically being on the order of the crystal lattice spacing, is smaller than the wavelength of magnetostatic spin waves in thin films, which is sub- to several micrometers.¹⁸ Therefore, a DW can act as an abrupt magnetic boundary for spin waves to see reflection and refraction of spin waves. A previous work

in micromagnetic simulation reports that the anisotropy in the dispersion relation of dipole-exchange spin waves results in the anomaly in the refraction compared to that in usual optics.¹⁹ Although the anisotropy appears prominently in the magnetostatic region, investigation on refraction and reflection dynamics of pure magnetostatic spin waves at the domain wall has yet to be investigated thoroughly.

In the present work, we report on experimental observations of the refraction and reflection of magnetostatic spin waves by a 90° DW in a ferrite garnet film (FGF). At such a domain wall, the dispersion relation of magnetostatic spin waves rotates in-plane by 90° because in-plane orientation of $\mathbf{M}$ determines the axis of symmetry for a dispersion relation.¹⁸ The direct observation of the magnetostatic spin waves by time-resolved magneto-optical imaging, and subsequent analysis of the observed images, reveals the refraction law of magnetostatic spin waves at a 90° DW. In ordinary refraction between two different media with positive refraction indices, the refracted wave has a wavevector pointing forward along the boundary. Above a certain incident angle, we find that the refracted spin waves have a wavevector directed backward along the DW. This behavior is similar to having a negative refraction index, i.e., refraction between media with refraction indices of opposite signs.^{20,21}

In this work, we used a 3- μm thick Bi-substituted ferrite garnet film with the composition $\text{Bi}_{0.7}\text{Lu}_{2.3}\text{Fe}_{4.2}\text{Ga}_{0.8}\text{O}_{12}$ (LuIG).^{22,23} This sample is a ferrimagnetic insulator having an in-plane spontaneous magnetization ($M_s = 62.7 \text{ kA/m}$) due to the negative uniaxial anisotropy along the direction normal to the sample surface ($K_u = -96 \text{ J/m}^{-3}$).²⁴ In the absence of an external magnetic field, the Neel-type 90° domain wall (DW) is formed. This DW can be pinned by the crystallographic defects in the sample. In our experiment, no magnetic field is applied so that DW is formed in the sample. The formation of magnetic domains has been confirmed by using the Cotton-Mouton effect (CME).²⁵ The width of the DW, δ , is estimated to be 400 nm using the relation $\delta = \pi\sqrt{A/K_c}$, where $A = 3.7 \text{ pJ/m}$ is the exchange coupling constant and $K_c = 1.8 \text{ J/m}^3$ is the cubic anisotropy of the sample. In our experiments, spin waves are excited by illuminating the sample with an 800 nm laser pulse (pump beam). The excitation and propagation dynamics of spin waves are observed using a time-resolved magneto-optical imaging system based on the pump-and-probe technique and a rotation analyzer method using a CCD camera (Fig. 1).²⁶ The spatial resolution of the images is $1 \mu\text{m}$. This setup measures the Faraday rotation angle of the transmitted light from a pulsed laser with the wavelength of 630 nm (probe beam). By taking the difference between the images recorded with and without the pump beam illumination, we find the spatiotemporal magnetization change along the sample depth direction excited by the pump beam. The observed spin waves are analyzed with a model based on Fourier transform, called spin-wave tomography (SWaT).²⁴

In order to investigate the interplay between a DW and propagating spin waves, we used planar propagating spin waves generated by the illumination of a pump beam. In these experiments, spin waves were generated by the optically excited elastic waves through magnetoelastic coupling (MEC).^{27,28} The amplitude of spin waves excited via MEC is resonantly enhanced at the crossing of the dispersion curves of spin waves and elastic waves. This determines the wavenumber and frequency of the dominant spin wave propagation.²⁹ In the experiment, we chose the wavevector of elastic waves by using a slit, making the focus of the pump beam elliptical. As a result, almost planar spin waves with very narrow $\mathbf{k}$ and ω distributions are obtained.

Consider first the 90° DW observed by the Cotton-Mouton effect (CME) as shown in Fig. 2(a). CME refers to a magnetic birefringence

effect which induces light ellipticity to the transmitted light. Two magnetic domains (MDs) separated by a DW are clearly observed. We here name these domains MD1 and MD2, as defined in Fig. 2(a). The orientation of magnetization is determined by CME observed as a function of the polarization angle of the incident probe beam [Fig. 2(b)]. The light ellipticity obtained in MD1 and MD2 shows almost equal magnitudes and opposite signs, implying that the magnetization orientations in MD1 and MD2 are orthogonal.

Next, we consider the spin wave propagation across the DW. These waves are excited by illuminating the sample with a pump beam in MD1. The propagation dynamics of the spin waves are shown of Fig. 2(c). In MD1, the spin waves propagate with the wave vector $\mathbf{k}_{\text{in}}$ as shown in the middle panel in Fig. 2(c). The propagation of spin waves is consistent with that observed in a single domain sample. The spin waves propagate across the DW and appear in MD2. Interestingly, the wavevector of the transmitted spin waves is opposite to what is expected for the ordinary

FIG. 2. (a) Static magneto-optical image obtained through the Cotton-Mouton effect which reveals the in-plane orientation of the magnetization. (b) The light ellipticity of the transmitted probe beam, reflecting the in-plane magnetization through the Cotton-Mouton effect, as a function of its polarization angle. The blue and red filled circles are obtained in MD1 and MD2, respectively. Solid line is the calculated polarization dependence for each domains.²⁵ (c) Magneto-optical images obtained at different time delays between pump beam and probe beam. The white arrow in the panels indicates the wavevector of the incident spin waves. The vertical dashed line indicates the position of the DW.

FIG. 1. (a) Schematic illustration of sample configuration. Spin waves are excited by illuminating the sample by the focused pump beam near a 90° domain wall. The angle of the incident, reflected, and refracted spin waves by the domain wall are referred to θ_{inc} , θ_{refl} , and θ_{refr} , respectively. (b) Schematic illustration of the time-resolved magneto-optical imaging. Faraday rotation angle of the transmitted probe beam is measured with the rotation analyzer method combined with a CCD camera.

refraction, as that of light at the interface between different media with positive refraction indices. Indeed, the spin waves in MD2 represent negative refraction by the DW.

The change in $\mathbf{k}$ of the spin waves at the DW is clearly seen also in the SWaT spectra. In order to distinguish spin waves propagating in MD1 and MD2, we applied a time window, given by a Gaussian function with the central time at t_c and a width of 1.0 ns, when calculating the SWaT spectra. Figure 3(a) shows a cross section of the obtained SWaT spectra at $f = 1.0$ GHz with $t_c = 2.5$ ns and 9.5 ns, respectively. In the top panel of Fig. 3(a), one sees a single strong peak representing the spin waves excited by the pump beam. On the other hand, in the bottom panel of Fig. 3(a), one sees two peaks at different $\mathbf{k}$ values. These two peaks are attributed to spin waves reflected and refracted by the 90° DW. In order to confirm the conservation of wavevector along

FIG. 3. (a) The SWaT spectra at $f = 1.0$ GHz obtained by filtering the time range of 2.0 ns to 3.0 ns (top panel) and 9.0 ns to 10.0 ns (bottom panel). The single peak of the incident spin waves is split into reflected and refracted spin waves after the incidence onto the DW. (b) The left panel shows the integration of the SWaT spectra with respect to the x component of wavevectors. Integration around the peak representing incident, refracted, and reflected spin waves is shown by filled blue, red and black circles. The right panel shows the integrated the SWaT spectra over $\mathbf{k}$ for different frequencies. The quadrant including the peak of incident, refracted, and reflected spin waves is used to obtain each spectrum. The gray solid line is the guide the eye in the both panels.

the DW (k_y) and frequency among the incident, refracted, and reflected waves, we show the integrated spectral intensity in Fig. 3(c). Here one sees that the k_y and the central frequency of these three waves are the same, thus satisfying the presupposition to derive Snell's law for spin waves at a 90° domain wall.

The conservation of k_y leads to a reflection and refraction rule for spin waves similar to Snell's law in geometrical optics. This is modeled as follows by the extension of the discussion on the Snell's law in a step-structured magnetic film.¹ First, we write the dispersion relation of spin waves by

$$\frac{\omega}{\mu_0 \gamma} = \sqrt{\left(H + M_s - \frac{Mkd}{2}\right) \left(H + M_s - \frac{M_s kd}{2} \sin^2 \theta_k\right)}, \quad (1)$$

where H , M_s , and d are the external magnetic field, saturation magnetization, and sample thickness, respectively. The contour of the dispersion relation at 1.0 GHz in MD1 is shown in Fig. 4(a) by blue solid lines. Since the orientation of the magnetization in MD2 is rotated by 90° compared to MD1, the dispersion relation in MD2 also rotates by 90° compared to that in MD1 as shown in Fig. 4(a) by red solid lines.

FIG. 4. (a) The red and blue lines represent the contour of spin-wave dispersion at 1.0 GHz in MD1 and MD2, respectively. (b) The experimentally obtained refracted angle as a function of incident angle is plotted by filled circles. Solid line shows the relation between refraction angle and incident angle with the model based on Eq. (1). (c) Relation between incident, refracted, and reflected wave in wavenumber space and real space for $\theta_{in} < \theta_c$. (d) Relation between incident, refracted, and reflected wave in wavenumber space and real space for $\theta_{in} > \theta_c$.

The experimentally determined relation between the incident angle (θ_{in}) and the refraction angle (θ_{refr}) at the DW is compared with our model calculation in Fig. 4(b). θ_{refr} increases rapidly for θ_{in} in the region satisfying $\theta_{\text{in}} > 0$, while it slowly changes for $\theta_{\text{in}} < 0$. The k_y and frequency conservation before and after the incidence onto a DW leads to the solid red line in Fig. 4(b), which shows agreement with the experimental data. Above the angle $\theta_c (= 20.4^\circ)$, θ_{refr} surpasses 90° . This means that the refracted waves propagate toward the inverse direction as compared to that in ordinary refraction between materials with positive refraction indices. Thus, the spin waves show negative refraction.

This unusual refraction of spin waves originates from the anisotropy of the dispersion relation and the consequent difference in the direction of the wavevector and group velocity. The relation between wavevectors of incident and refracted waves is schematically illustrated in Figs. 4(c) and 4(d). In the case of $\theta_{\text{in}} < \theta_c$, the refracted wave has negative k_x and k_y as seen in the left panel of the Fig. 4(c). The incident and refracted waves are chosen to propagate toward left, considering the group velocity shown by black arrows. In this case, both θ_{in} and θ_{refr} are less than 90° ; therefore, negative refraction does not occur as shown in the right panel of Fig. 4(c).

In the case of $\theta_{\text{in}} > \theta_c$, as shown in the left panel of Fig. 4(d), the refracted wave goes across the k_y axis and carries positive k_x . At this point, the θ_{refr} surpasses 90° . Although the wavevector of refracted spin waves directs toward MD1, the refracted wave propagates into MD2 because the group velocity of refracted waves still directs toward left. Therefore, the negative refraction of spin waves emerges in this case.

The discussion on the anisotropic dispersion relation and group velocity provides information on the transmission coefficient as well. One of the essentials for the observed refraction is the fact that direction of group velocity and wavevector is different. When spin waves incident with the incident angle of 45° , the group velocity and wavevector are parallel due to the symmetry of contour of the spin-wave dispersion relation. In this case, when the incident wavevector is taken so that the wave propagates toward left, the refracted wave has the group velocity toward right, leading no transmission of spin waves. This discussion can be confirmed from the continuity condition imposed to magnetic field around DW, just as the derivation of Fresnel's law for the light; however, it is out of focus for current work. Note that in our experiments, precise estimation of reflectivity and transmittance of spin waves is difficult because we observe the transient state of spin-wave propagation, and thus, the amplitude changes during the measurement time.

Note also that the spin wave ray, which represents the energy flow due to spin waves, shows negative refraction in both cases because refracted spin waves have opposite sign of the y component of the group velocity compared to the incident spin waves. The case of $\theta_{\text{in}} > \theta_c$ is special in that both wavevector and group velocity demonstrate negative refraction. In the region satisfying $\theta_{\text{in}} < 0$, negative refraction is not realized because the refracted state is limited to the region with negative k_x . Let us also note that our model does not consider the contribution of MEC at the DW. Their negligible contributions in the reflection and refraction of spin waves are implied by the agreement of our model with the experimental data. This is reasonable

since the energy scale of MEC is small compared to the energy of magnetostatic spin waves.

In summary, we have observed Snell's law and negative refraction of spin waves at a 90° magnetic domain wall in a magnetic garnet film. We observed propagation of spin waves crossing a 90° domain wall. The relation between refraction and incident angles is modeled by considering the anisotropic dispersion relation of spin waves in the magnetostatic regime and the wavenumber conservation of spin waves along the DW. The obtained results pave the way for manipulation of the wavevector of spin waves by using magnetic domain walls.

This work was financially supported by JST-ERATO (No. JPMJER1402) from JST, Japan, Grant-in-Aid for Scientific Research on Innovative Area "Nano Spin Conversion Science" (No. JP26103005) from JSPS KAKENHI, Japan, and World Premier International Research Center Initiative (WPI), Japan. T.H. was supported by JSPS through a research fellowship for young scientists (No. 18J21004) and acknowledges the support from GP-Spin at Tohoku University.

REFERENCES

- ¹J. Stigloher, M. Decker, H. S. Körner, K. Tanabe, T. Moriyama, T. Taniguchi, H. Hata, M. Madami, G. Gubbiotti, K. Kobayashi, T. Ono, and C. H. Back, *Phys. Rev. Lett.* **117**, 037204 (2016).
- ²K. Tanabe, R. Matsumoto, J. Ohe, S. Murakami, T. Moriyama, D. Chiba, K. Kobayashi, and T. Ono, *Appl. Phys. Exp.* **7**, 053001 (2014).
- ³P. Gruszecki, Y. S. Dadoenkova, N. N. Dadoenkova, I. L. Lyubchanskii, J. Romero-Vivas, K. Y. Guslienko, and M. Krawczyk, *Phys. Rev. B* **92**, 054427 (2015).
- ⁴W. Yu, J. Lan, R. Wu, and J. Xiao, *Phys. Rev. B* **94**, 140410 (R) (2016).
- ⁵Y. S. Dadoenkova, N. N. Dadoenkova, I. L. Lyubchanskii, M. L. Sokolovskyy, J. W. Klos, J. Romero-Vivas, and M. Krawczyk, *Appl. Phys. Lett.* **101**, 042404 (2012).
- ⁶K. Yasumoto and Y. Oishi, *J. Appl. Phys.* **54**, 2170 (1983).
- ⁷R. Gieniusz, V. D. Bessonov, U. Guzowska, A. I. Stognii, and A. Maziewski, *Appl. Phys. Lett.* **104**, 082412 (2014).
- ⁸Y. I. Gorobets and S. A. Reshetnyak, *Tech. Phys.* **43**, 188 (1998).
- ⁹D.-E. Jeong, D.-S. Han, and S.-K. Kim, *Spin* **1**, 27 (2011).
- ¹⁰K. Vogt, F. Y. Fradin, J. E. Pearson, T. Sebastian, S. D. Bader, B. Hillebrands, A. Hoffmann, and H. Schultheiss, *Nat. Commun.* **5**, 3727 (2014).
- ¹¹F. Heussner, A. A. Serga, T. Brächer, B. Hillebrands, and P. Pirro, *Appl. Phys. Lett.* **111**, 122401 (2017).
- ¹²R. Hertel, W. Wulfhekel, and J. Kirschner, *Phys. Rev. Lett.* **93**, 257202 (2004).
- ¹³K. Wagner, A. Kákay, K. Schultheiss, A. Henschke, T. Sebastian, and H. Schultheiss, *Nat. Nanotechnol.* **11**, 432–436 (2016).
- ¹⁴S. J. Hermesdoerfer, H. Schultheiss, C. Rausch, S. Schäfer, B. Leven, S.-K. Kim, and B. Hillebrand, *Appl. Phys. Lett.* **94**, 223510 (2009).
- ¹⁵S. Zhang, C. Mu, Q. Zhu, Q. Zheng, X. Liu, J. Wang, and Q. Liu, *J. Appl. Phys.* **115**, 013908 (2014).
- ¹⁶X.-G. Wang, G.-H. Guo, G.-F. Zhang, Y.-Z. Nie, and Q.-L. Xia, *J. Appl. Phys.* **113**, 213904 (2013).
- ¹⁷B. V. v. Wiele, S. J. Hämäläinen, P. Baláz, F. Montoncello, and S. V. Dijken, *Sci. Rep.* **6**, 21330 (2016).
- ¹⁸M. J. Hurben and C. E. Patton, *J. Magn. Magn. Mater.* **163**(1), 39 (1996).
- ¹⁹S.-K. Kim, S. Choi, K.-S. Lee, D.-S. Han, D.-E. Jung, and Y.-S. Choi, *Appl. Phys. Lett.* **92**, 212501 (2008).
- ²⁰D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, *Science* **305**, 5685 (2004).
- ²¹V. M. Shalaev, *Nat. Phys.* **1**, 41–48 (2007).
- ²²L. E. Helseth, R. W. Hansen, E. I. Il'yashenko, M. Baziljevich, and T. H. Johansen, *Phys. Rev. B* **64**, 174406 (2001).

- ²³L. E. Helseth, A. G. Solov'yev, R. W. Hansen, E. I. Il'yashenko, M. Baziljevich, and T. H. Johansen, *Phys. Rev. B* **66**, 064405 (2002).
- ²⁴Y. Hashimoto, S. Daimon, R. Iguchi, Y. Oikawa, K. Shen, K. Sato, D. Bossini, Y. Tabuchi, T. Satoh, B. Hillebrands, G. E. W. Bauer, T. H. Johansen, A. Kirilyuk, T. Rasing, and E. Saitoh, *Nat. Commun.* **8**, 15859 (2017).
- ²⁵T. Hioki, Y. Hashimoto, T. H. Johansen, and E. Saitoh, *Phys. Rev. Appl.* **11**, 061007 (2019).
- ²⁶Y. Hashimoto, A. R. Khorsand, M. Savoini, B. Koene, D. Bossini, A. Tsukamoto, A. Itoh, Y. Ohtsuka, K. Aoshima, A. V. Kimel, A. Kirilyuk, and T. Rasing, *Rev. Sci. Instrum.* **85**, 063702 (2014).
- ²⁷C. Kittel, *Phys. Rev.* **110**, 836 (1958).
- ²⁸N. Ogawa, W. Koshibae, A. J. Beekmana, N. Nagaosa, M. Kubota, M. Kawasaki, and Y. Tokura, *Proc. Natl. Acad. Sci. U. S. A.* **112**(29), 8977–8981 (2015).
- ²⁹Y. Hashimoto, D. Bossini, T. H. Johansen, E. Saitoh, A. Kirilyuk, and T. Rasing, *Phys. Rev. B* **97**, 140404(R) (2018).