Spin torque effect on spin waves in a ferromagnetic layer

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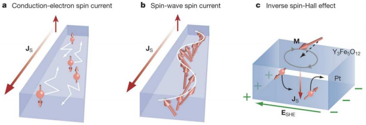
- Project NANOSPIN PSPB-045/2010 supported by a grant from Switzerland through the Swiss Contribution to the enlarged European Union
- National Science Center in Poland as the Project No. DEC-2012/04/A/ST3/00372
- Czech Science Foundation as the Grant 15-08740Y

Outline

Motivation



Y. Kajiwara *et al.*
Transmission of electrical signals by spin-wave interconversion in a magnetic insulator
Nature **464**, 262 (2010)

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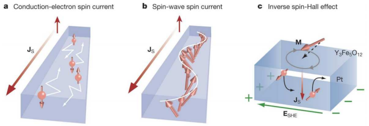

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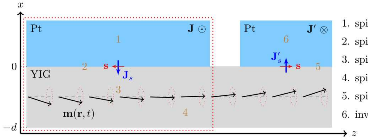

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Physical Review B **88**, 184403 (2013)

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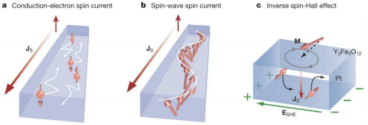

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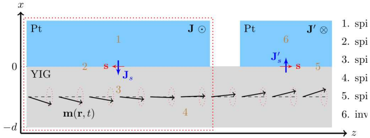

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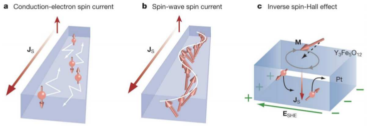

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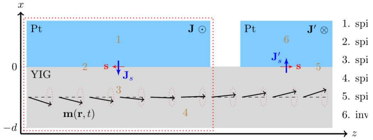

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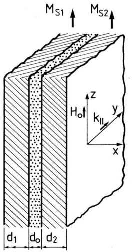
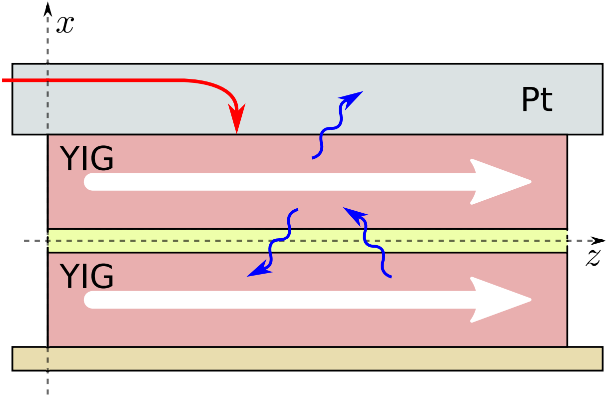


M. Vohl, J. Barnaś, and P. Grünberg
Effect of interlayer exchange coupling on spin-wave spectra in magnetic double layers: Theory and experiment
Physical Review B **39**, 12003 (1989)

Outline

YIG double layer

- Spin current due to spin–orbit coupling in Pt layer
- Spin pumping due to spin dynamics in YIG layers



Bulk dynamics

Landau-Lifshitz-Gilbert equation

$$\frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t} = -\gamma_j \mu_0 \mathbf{M}_j \times \mathbf{H}_{\mathrm{eff}\,j} + \frac{\alpha_j}{M_{\mathrm{s}j}} \mathbf{M}_j \times \frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t}$$

Effective magnetic field in j-th layer

$$\mathbf{H}_{\mathrm{eff}\,j}(\mathbf{r},t) = H_0\,\hat{e}_z + \frac{H_{\mathrm{a}j}}{M_{\mathrm{s}j}} \left[\mathbf{M}_j(\mathbf{r},t)\cdot\hat{e}_z\right]\hat{e}_z + \mathbf{h}_j(\mathbf{r},t) + \frac{2A_j}{\mu_0 M_{\mathrm{s}j}^2}\nabla^2\mathbf{M}_j(\mathbf{r},t)$$

Bulk dynamics

Landau-Lifshitz-Gilbert equation

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approximation: $\mathbf{M}_j(\mathbf{r},t) = s_j M_{\mathrm{s}j}\hat{e}_z + \mathbf{m}_j(\mathbf{r},t)$, where $\mathbf{m}_j(\mathbf{r},t) = (m_{j,x}(\mathbf{r},t), m_{j,y}(\mathbf{r},t), 0)$

Bulk dynamics

Landau-Lifshitz-Gilbert equation

$$\frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t} = -\gamma_j \mu_0 \mathbf{M}_j \times \mathbf{H}_{\mathrm{eff}j} + \frac{\alpha_j}{M_{\mathrm{s}j}} \mathbf{M}_j \times \frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t}$$

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Magnetostatic scalar potential

$$\mathbf{h}_j(\mathbf{r}) = -\nabla\psi_j(\mathbf{r})$$

$$\nabla^2\psi_j - \left(\frac{\partial m_{j,x}}{\partial x} + \frac{\partial m_{j,y}}{\partial y}\right) = 0$$

Dynamic variables

$$\mathbf{m}_j(\mathbf{r},t) = \mathbf{m}_j(\mathbf{r})\,e^{-i\omega t}$$

$$\psi_j(\mathbf{r},t) = \psi_j(\mathbf{r})\,e^{-i\omega t}$$

Bulk dynamics

Solutions

$$m_{j,x}(\mathbf{r}) = e^{i q_y y} \sum_{l=1}^{3} \left[C_{j,1}^{(l)} \cos(k_{j,l}x) + D_{j,1}^{(l)} \sin(k_{j,l}x) \right]$$

$$m_{j,y}(\mathbf{r}) = e^{i q_y y} \sum_{l=1}^{3} \left[C_{j,2}^{(l)} \cos(k_{j,l}x) + D_{j,2}^{(l)} \sin(k_{j,l}x) \right]$$

$$\psi_j(\mathbf{r}) = e^{i q_y y} \sum_{l=1}^{3} \left[C_{j,3}^{(l)} \cos(k_{j,l}x) + D_{j,3}^{(l)} \sin(k_{j,l}x) \right]$$

Wave vectors

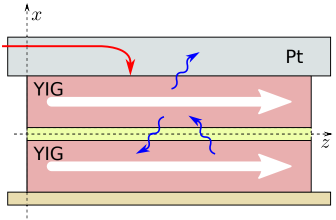
$$k_{j,1}^2 = -\, q_y^2$$

$$k_{j,2(3)}^2 = -\frac{\mu_0 M_{\mathrm{s}j}^2}{2A_j} \left[1/2 + \frac{H_{\mathrm{a}j}}{M_{\mathrm{s}j}} + \frac{H_0}{M_{\mathrm{s}j}} - i\,\alpha_j f_j \pm \sqrt{f_j^2 + (1/2)^2} \right] - q_y^2$$

where $f_j = \omega/(\mu_0 \gamma_j M_{\mathrm{s}j})$.

Boundary conditions

4 interfaces



$$x_{i1} = L_1 + L_s/2$$
$$x_{i2} = L_s/2$$
$$x_{i3} = -L_s/2$$
$$x_{i4} = -(L_2 + L_s/2)$$

- Interface anisotropy at the interface between top YIG and Pt layer
- Interlayer exchange coupling (RKKY) between the YIG layers
- Spin pumping from top YIG to Pt layer
- Dynamic coupling between YIG layers due to spin pumping into the spacer
- Spin transfer torque due to spin current from Pt layer

External interfaces

Landau-Lifshitz-Gilbert equation

$$\frac{\mathrm{d}\mathbf{M}_1}{\mathrm{d}t} = -\gamma_1 \mu_0 \mathbf{M}_1 \times \mathbf{H}_{\mathrm{eff}\,i1} + \frac{\alpha_1}{M_{\mathrm{s}\,1}} \mathbf{M}_1 \times \frac{\mathrm{d}\mathbf{M}_1}{\mathrm{d}t} + \frac{\gamma_1}{M_{\mathrm{s}\,1}} \left(\boldsymbol{\tau}_{\mathrm{STT}\,i1} + \boldsymbol{\tau}_{\mathrm{SP}\,i1} \right)$$

Effective magnetic field

$$\mathbf{H}_{\mathrm{eff}\,i1} = H_0 \hat{e}_z + \mathbf{h}_1(\mathbf{r},t) + \frac{2A_1}{\mu_0 {M_{\mathrm{s}}}_1^2} \nabla^2 \mathbf{M}_1 - \frac{2{K^{\mathrm{s}}}_1}{\mu_0 {M_{\mathrm{s}}}_1^2 \delta} (\mathbf{M}_1 \times \hat{n}_1)\hat{n}_1$$

Spin transfer torque

$$\boldsymbol{\tau}_{\mathrm{STT}\,i1} = \frac{J_{\mathrm{s}}}{M_{\mathrm{s}\,1}\delta} \mathbf{M}_1 \times \hat{e}_z \times \mathbf{M}_1$$

Spin pumping

$$\boldsymbol{\tau}_{\mathrm{SP}\,i1} = \frac{g_{\mathrm{r}\,1}\hbar}{4\pi\delta} \frac{\mathbf{M}_1}{M_{\mathrm{s}\,1}} \times \frac{\mathrm{d}\mathbf{M}_1}{\mathrm{d}t}$$

External interfaces

Rado-Weertman boundary conditions

Top interface ($x = x_{i1}$)

$$\left(A_1 \frac{\partial}{\partial x} - i\, G_1\, \omega\right) m_{1,y} - \frac{J_s}{2} m_{1,x} \,|_{x_{i1}} = 0$$

$$\left(A_1 \frac{\partial}{\partial x} - i\, G_1\, \omega - K^{s}{}_1\right) m_{1,x} + \frac{J_s}{2} m_{1,y} \,|_{x_{i1}} = 0.$$

- Spin pumping: G_1 (mixing conductance)
- Spin transfer torque: J_s (spin current)

External interfaces

Rado-Weertman boundary conditions

Top interface ($x = x_{i1}$)

$$\left(A_1 \frac{\partial}{\partial x} - i\, G_1\, \omega\right) m_{1,y} - \frac{J_s}{2} m_{1,x} \,|_{x_{i1}} = 0$$

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- Spin pumping: G_1 (mixing conductance)
- Spin transfer torque: J_s (spin current)

Bottom interface ($x = x_{i4}$)

$$\frac{\partial}{\partial x} m_{2,y} \,|_{x_{i4}} = 0$$

$$\frac{\partial}{\partial x} m_{2,x} \,|_{x_{i4}} = 0$$

Internal interfaces

Landau-Lifshitz-Gilbert equation

$$\frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t} = -\gamma_j \mu_0 \mathbf{M}_j \times \mathbf{H}_{\mathrm{eff}}{}'_j + \frac{\alpha_j}{M_{\mathrm{s}j}} \mathbf{M}_j \times \frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t} + \frac{\gamma_j}{M_{\mathrm{s}j}} \boldsymbol{\tau}_{\mathrm{DC}j}$$

Effective magnetic field

$$\mathbf{H}_{\mathrm{eff}}{}'_j = H_0 \hat{e}_z + \mathbf{h}_j(\mathbf{r},t) + \frac{2A_j}{\mu_0 M_{\mathrm{s}j}^2} \nabla^2 \mathbf{M}_j - \frac{2A_{12}}{\mu_0 M_{\mathrm{s}j} M_{\mathrm{s}i} \delta} \mathbf{M}_i$$

Dynamic coupling

$$\boldsymbol{\tau}_{\mathrm{DC}j} = \frac{\hbar g_{\mathrm{r}}}{4\pi\delta} \left(\frac{\mathbf{M}_j}{M_{\mathrm{s}j}} \times \frac{\mathrm{d}\mathbf{M}_j}{\mathrm{d}t} - \frac{\mathbf{M}_i}{M_{\mathrm{s}i}} \times \frac{\mathrm{d}\mathbf{M}_i}{\mathrm{d}t} \right)$$

Mixing conductance

$$\frac{1}{g_{\mathrm{r}}} = \frac{1}{g_{\mathrm{r}i2}} + \frac{1}{g_{\mathrm{r}i3}}$$

Internal interfaces

Hoffmann conditions

First couple

$$\left(\frac{A_1}{M_{s1}}\frac{\partial}{\partial x} - \frac{A_{12}}{M_{s1}} + i\frac{G_{12}}{M_{s1}}\omega\right) m_{1,y}\,|_{x_{i2}} + \left(\frac{A_{12}}{M_{s2}} - i\frac{G_{12}}{M_{s1}}\omega\right) m_{2,y}\,|_{x_{i3}} = 0$$

$$\left(\frac{A_1}{M_{s1}}\frac{\partial}{\partial x} - \frac{A_{12}}{M_{s1}} + i\frac{G_{12}}{M_{s1}}\omega\right) m_{1,x}\,|_{x_{i2}} + \left(\frac{A_{12}}{M_{s2}} - i\frac{G_{12}}{M_{s1}}\omega\right) m_{2,x}\,|_{x_{i3}} = 0$$

Second couple

$$\left(\frac{A_2}{M_{s2}}\frac{\partial}{\partial x} + \frac{A_{12}}{M_{s2}} - i\frac{G_{12}}{M_{s2}}\omega\right) m_{2,y}\,|_{x_{i3}} - \left(\frac{A_{12}}{M_{s1}} - i\frac{G_{12}}{M_{s2}}\omega\right) m_{1,y}\,|_{x_{i2}} = 0$$

$$\left(\frac{A_2}{M_{s2}}\frac{\partial}{\partial x} + \frac{A_{12}}{M_{s2}} - i\frac{G_{12}}{M_{s2}}\omega\right) m_{2,x}\,|_{x_{i3}} - \left(\frac{A_{12}}{M_{s1}} - i\frac{G_{12}}{M_{s2}}\omega\right) m_{1,x}\,|_{x_{i2}} = 0$$

- Static interlayer coupling: A_{12} (RKKY exchange coupling)
- Dynamic interlayer coupling: G_{12} (mixing conductance)

Continuity of dipolar-exchange field and magnetization

tangential component of $\mathbf{h}_j(\mathbf{r})$ and the normal component of $\mathbf{h}_j(\mathbf{r}) + \mathbf{m}_j(\mathbf{r})$ must be continuous across the interfaces

External interfaces

$$\left(\frac{\partial}{\partial x} + q\right)\psi_1 - m_{1,x}\,|_{x_{i1}} = 0$$

$$\left(\frac{\partial}{\partial x} - q\right)\psi_2 - m_{2,x}\,|_{x_{i4}} = 0$$

Internal interfaces

$$e^{-qL_s/2}\left[\left(q - \frac{\partial}{\partial x}\right)\psi_1 + m_{1,x}\right]_{x_{i3}} = e^{qL_s/2}\left[\left(q - \frac{\partial}{\partial x}\right)\psi_2 + m_{2,x}\right]_{x_{i2}}$$

$$e^{qL_s/2}\left[\left(q + \frac{\partial}{\partial x}\right)\psi_1 - m_{1,x}\right]_{x_{i3}} = e^{-qL_s/2}\left[\left(q + \frac{\partial}{\partial x}\right)\psi_2 - m_{2,x}\right]_{x_{i2}}$$

Calculation of the eigenfrequencies

- We have 12 boundary conditions with 12 unknown variables $C_{j,1}^{(l)}$ and $D_{j,1}^{(l)}$.

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$$\det \bar{\mathbf{M}} = 0$$

where $\bar{\mathbf{M}}$ is matrix of the boundary conditions.

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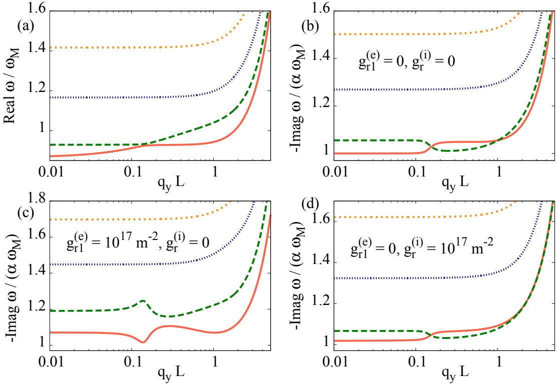
- The system of linear equation has nontrivial solution when

$$\det \bar{\mathbf{M}} = 0$$

  where $\bar{\mathbf{M}}$ is matrix of the boundary conditions.
- we find numerically $\omega = \omega_{\mathrm{r}} + i\,\omega_{\mathrm{i}}$ satisfying the condition.

Outline

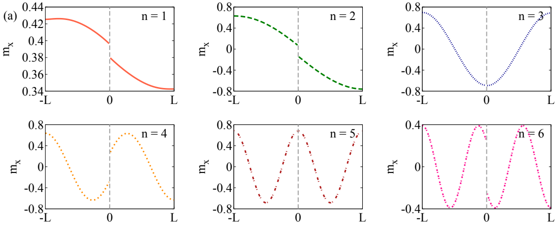
Spin wave spectra



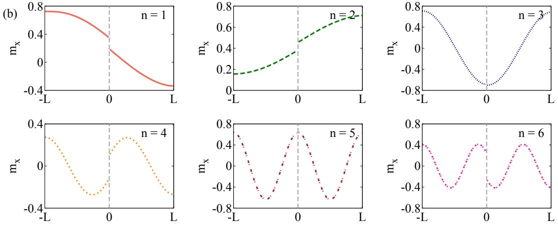
(a) real part of ω, (b) no spin pumping, (c) spin pumping at the top interface, (d) spin pumping through the spacer

Spin wave profiles

$q_y L = 0.1$

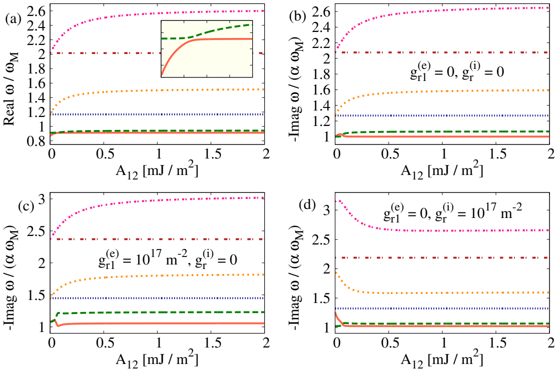


$q_y L = 0.3$



Dependence on interlayer coupling A_{12}

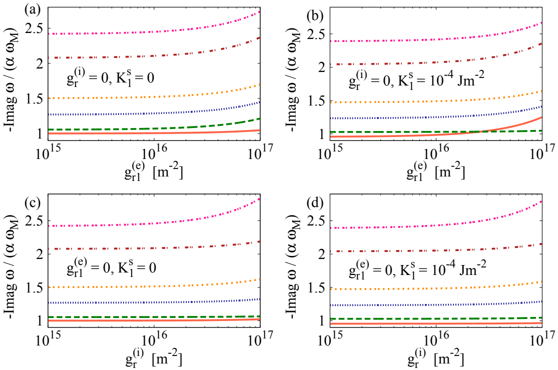
$q_y L = 0.1$



(a) real part of ω, (b) no spin pumping, (c) spin pumping at the top interface, (d) spin pumping through the spacer

Influence of mixing conductance

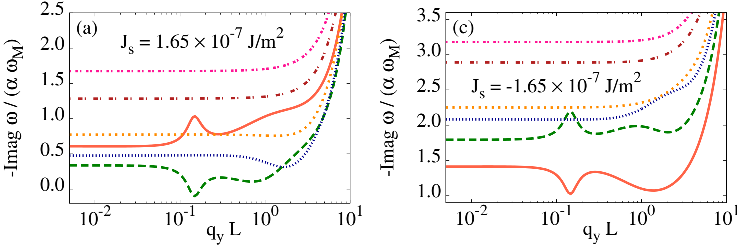
$q_y L = 0.1$



(a), (c) function of spin pumping at the top interface, (b), (d) function of spin pumping through the spacer

Influence of spin current

$q_y L = 0.1$



- Positive spin current destabilizes spin wave modes
- Negative spin current stabilizes spin wave modes

Outline

Summary

- Possibility of manipulation with spin wave damping by means of spin pumping in a YIG double layer has been demonstrated.
- Dynamic interlayer coupling influences mostly optical spin wave modes.
- Spin current can enhance life time of spin waves in a nonlinear way.

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Thank you for your attention!