SWISS CONTRIBUTION

NANOSPIN

Spin current assisted magnetization dynamics in exchange coupled magnetic layers

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Partners

- AGH University of Science and Technology in Kraków
  T. Stobiecki – coordinator
- Institute of Molecular Physics in Poznań, Polish Academy of Sciences
  J. Dubowik – experiment, J. Barnaś – theory
- Ecolé Polytechnique Fédérale in Lausanne
  J.-Ph. Ansermet

Objectives

jointly developing novel nanoscale spintronic devices based on the spin transfer torque effect, which promises unrivaled future scaling, flexibility and low power consumption

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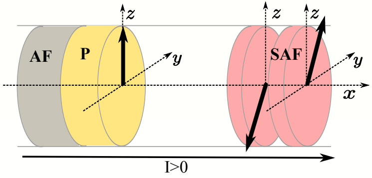
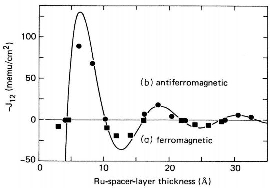
IFM PAN

Why double layers?

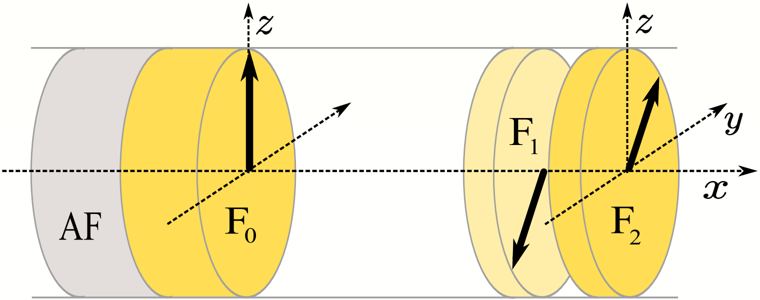




S.S.P. Parkin, D. Mauri
Spin engineering: Direct determination of the Ruderman-Kittel-Kasuya-Yosida far-field range function in ruthenium
Phys. Rev. B **44**, 7131 (1991)

- Double layer has high stability, $\Delta = \dfrac{E}{k_\mathrm{B}T} > 40$
- Reduction of critical current

Spin valve with composite free layer (CFL)



Magnetization dynamics

Landau-Lifshitz-Gilbert equation

$$\frac{\mathrm{d}\hat{S}_i}{\mathrm{d}t} + \alpha\,\hat{S}_i \times \frac{\mathrm{d}\hat{S}_i}{\mathrm{d}t} = \boldsymbol{\Gamma}_i\,, \qquad \boldsymbol{\Gamma}_i = -|\gamma_\mathrm{g}|\mu_0\hat{S}_i \times \mathbf{H}_{\mathrm{eff}\,i} + \frac{|\gamma_\mathrm{g}|}{M_\mathrm{s}d_i}\,\boldsymbol{\tau}_i$$

Effective magnetic field

$$\mathbf{H}_{\mathrm{eff}\,i} = -H_\mathrm{app}\,\hat{\mathbf{e}}_z - H_\mathrm{ani}(\hat{S}_i\cdot\hat{\mathbf{e}}_z)\,\hat{\mathbf{e}}_z + \mathbf{H}_{\mathrm{dem}\,i}(\hat{S}_i) + H_{\mathrm{RKKY}\,i}\,\hat{S}_j$$

Interlayer exchange coupling $H_{\mathrm{RKKY}\,i} = -J_\mathrm{RKKY}/(\mu_0 M_\mathrm{s} d_i)$

Spin transfer torque

$$\boldsymbol{\tau}_{1\|} = I\hat{S}_1 \times \left[\hat{S}_1 \times \left(a_1^{(0)}\hat{S}_0 + a_1^{(2)}\hat{S}_2\right)\right]$$

$$\boldsymbol{\tau}_{1\perp} = I\hat{S}_1 \times \left(b_1^{(0)}\hat{S}_0 + b_1^{(2)}\hat{S}_2\right)$$

$$\boldsymbol{\tau}_{2\|} = Ia_2^{(1)}\,\hat{S}_2 \times (\hat{S}_2 \times \hat{S}_1)$$

$$\boldsymbol{\tau}_{2\perp} = Ib_2^{(1)}\,\hat{S}_2 \times \hat{S}_1$$

Linearized Landau-Lifshitz-Gilbert equation

Static points of the dynamics

AP configuration $\uparrow$ $\downarrow\uparrow$ $\hat{S}_1 = (0,0,-1)$, $\hat{S}_2 = (0,0,1)$

P configuration $\uparrow$ $\uparrow\downarrow$ $\hat{S}_1 = (0,0,1)$, $\hat{S}_2 = (0,0,-1)$

Linearized LLG

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\delta}\tilde{S} = \bar{D}\cdot\boldsymbol{\delta}\tilde{S}\,, \text{ where } \quad \bar{D} = \begin{pmatrix} D_1 & C_{12} \\ C_{21} & D_2 \end{pmatrix}$$

single spin dynamic matrix:

$$D_i = \begin{pmatrix} \omega_i^\tau - \alpha\,\omega_i^{h1} & \alpha\,\omega_i^\tau - \omega_i^{h2} \\ -\alpha\,\omega_i^\tau - \omega_i^{h1} & \omega_i^\tau + \alpha\,\omega_i^{h2} \end{pmatrix}$$

coupling between the free layer's:

$$C_{ij} = \begin{pmatrix} -\omega_{ij}^\tau + \alpha\,\omega_{Ji} & -\left(\alpha\,\omega_{ij}^\tau + \omega_{Ji}\right)\cos\Delta\phi \\ \alpha\,\omega_{ij}^\tau + \omega_{Ji} & -\left(\omega_{ij}^\tau - \alpha\,\omega_{Ji}\right)\cos\Delta\phi \end{pmatrix}$$

Stability analysis

Lyapunov criterion

Static state, $\tilde{S}_0$, is stable if and only if all the eigenvalues of $\bar{D}$ have negative real parts. If one of them becomes positive, the static point is unstable.

Drawback: We do not have general expressions for the eigenvalues.

$$P(\lambda) = \det(\bar{D} - \lambda\bar{I}) = \lambda^4 + c_3\lambda^3 + c_2\lambda^2 + c_1\lambda + c_0$$

$$H_P = \begin{pmatrix} c_1 & c_0 & 0 & 0 \\ c_3 & c_2 & c_1 & c_0 \\ 0 & 1 & c_3 & c_2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

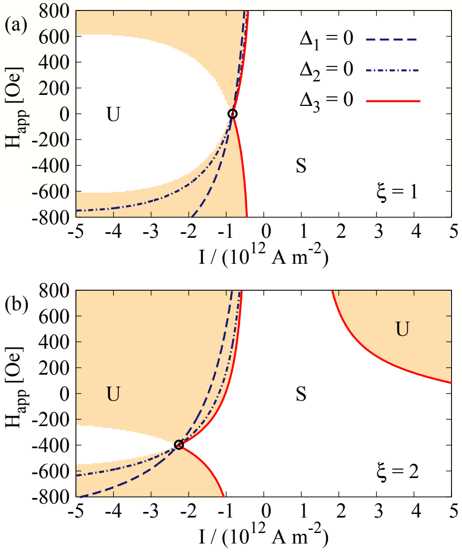
Routh-Hurwitz theorem

The roots of polynomial $P(\lambda)$ have all negative real parts if and only if all the leading principal minors of H_P are positive.

$$\Delta_1 = c_1 > 0, \quad \Delta_2 = \det\begin{pmatrix} c_1 & c_0 \\ c_3 & c_2 \end{pmatrix} > 0, \quad \Delta_3 = \det\begin{pmatrix} c_1 & c_0 & 0 \\ c_3 & c_2 & c_1 \\ 0 & 1 & c_3 \end{pmatrix} > 0$$

Results

Hurwitz determinants for AP configuration



(a) Synthetic antiferromagnet ($\xi = d_1/d_2 = 1$)

(b) Synthetic ferrimagnet ($\xi = 2$)

- in **S** area all the HDs are positive
- Δ_3 is the first HD which becomes negative
- lines Δ_i for $i = 1, 2, 3$ intersects in the same point

P. Baláž and J. Barnaś
Physical Review B 88, 014406 (2013)

Hurwitz determinants

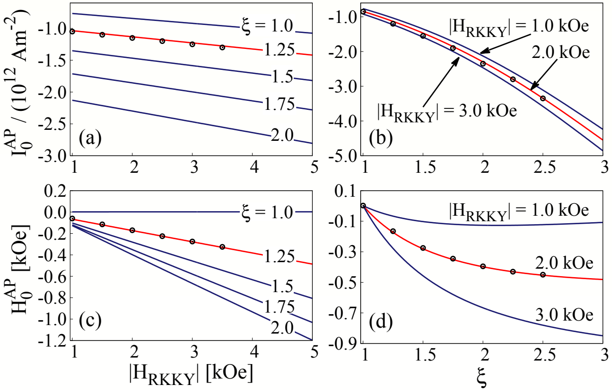
We observe that

- The critical current can be obtained from the condition $\boxed{\Delta_3 = 0}$.
- All three Hurwitz determinants intersects in the same point(s).
  When $\Delta_1 = c_1 = 0$ then $\Delta_2 = c_0 c_3$ and $\Delta_3 = c_0 c_3^2$.
  Intersection points:
  (i) $c_1 = 0$ and $c_3 = 0$
  (ii) $c_1 = 0$ and $c_0 = 0$
- Existence of double point in (i).
  $\partial\Delta_3/\partial I = \partial\Delta_3/\partial H_{\rm app} = 0$ only in the intersection point (i)
- The maximum critical current is given by $\boxed{c_3 = {\rm Tr}\bar{D} = 0}$ and correspondent field can be obtained from $\boxed{c_1 = 0}$.

Critical current density in AP configuration

$$I_0^{\rm AP} = -\alpha \frac{\mu_0 M_{\rm s}\, \xi\, d}{a_1^{(0)} + a_1^{(2)} + \xi\, a_2^{(1)}} \left[2H_{\rm ani} + H_1^{\rm d} + H_2^{\rm d} - (1+\xi^{-1}) H_{\rm RKKY} \right]$$

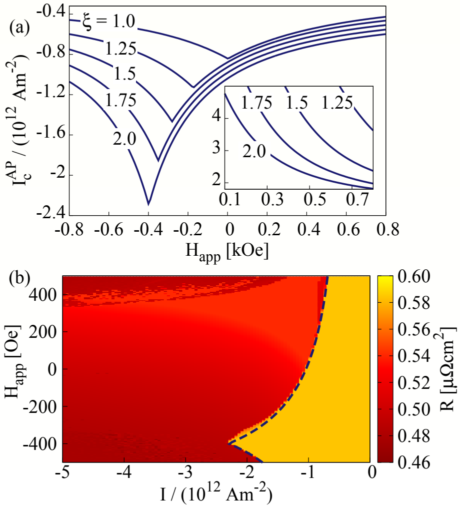
Results



I_0^{AP} / (10^{12} Am^{-2})
ξ = 1.0
1.25
1.5
1.75
2.0
(a)
|H$_{RKKY}$| = 1.0 kOe
2.0 kOe
|H$_{RKKY}$| = 3.0 kOe
(b)
H_0^{AP} [kOe]
ξ = 1.0
1.25
1.5
1.75
2.0
(c)
|H$_{RKKY}$| = 1.0 kOe
2.0 kOe
3.0 kOe
(d)
|H$_{RKKY}$| [kOe]
ξ

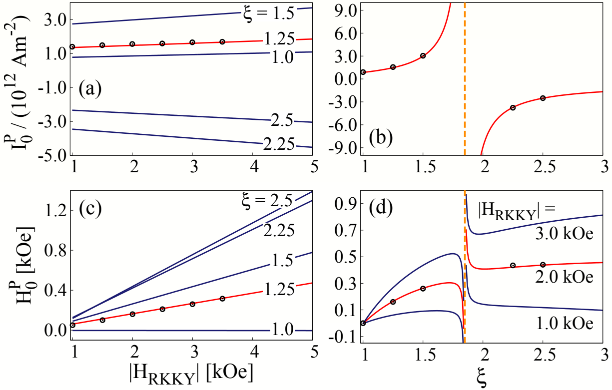
Results

Critical current density and comparison with numerical simulations



Results

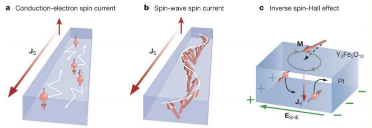
Critical current density in the opposite configuration



Critical asymmetry $a_1^{(0)}(\xi_c) - a_1^{(2)}(\xi_c) - \xi_c\, a_2^{(1)}(\xi_c) = 0$

In the studied device $\xi_c \simeq 1.85$.

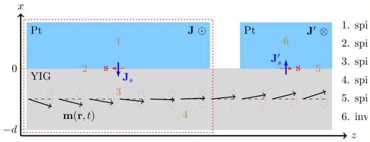
Motivation



Y. Kajiwara *et al.*

Transmission of electrical signals by spin-wave interconversion in a magnetic insulator

Nature **464**, 262 (2010)



Y. Zhou *et al.*

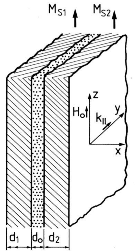
Current-induced spin-wave excitation in Pt/YIG bilayer

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

A. Kapelrud and A. Brataas.

Spin Pumping and Enhanced Gilbert Damping in Thin Magnetic Insulator Films

Physical Review Letters **111**, 097602 (2013)

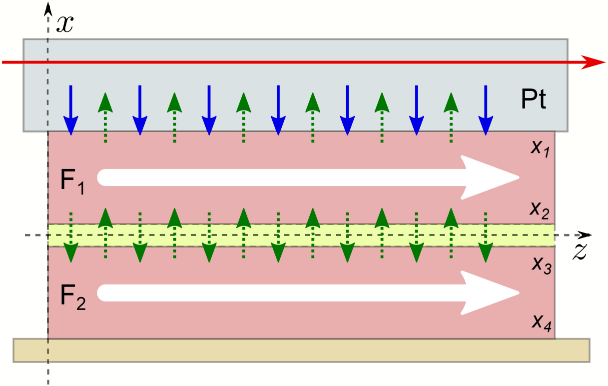


M. Vohl, J. Barnaś, and P. Grünberg

Effect of interlayer exchange coupling on spin-wave spectra in magnetic double layers: Theory and experiment

Physical Review B **39**, 12003 (1989)

YIG double layer



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

$$\mathbf{H}_{\mathrm{eff}\,j}(\mathbf{r},t) = s_0 \, H_0 \, \hat{e}_z + \frac{H_{\mathrm{a}j}}{M_{\mathrm{s}j}} \left[\mathbf{M}_j(\mathbf{r},t) \cdot \hat{e}_z\right] \hat{e}_z + \mathbf{h}_j(\mathbf{r},t) + \frac{2A_j}{\mu_0 M_{\mathrm{s}j}^2} \nabla^2 \mathbf{M}_j(\mathbf{r},t)$$

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

Dynamic variables

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

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

Maxwell equations

$$\nabla \times \mathbf{h}_j(\mathbf{r}) = 0$$

$$\nabla \cdot \left[\mathbf{h}_j(\mathbf{r}) + \mathbf{m}_j(\mathbf{r})\right] = 0$$

Bulk dynamics

Magnetostatic scalar potential:

$\mathbf{h}_j(\mathbf{r}) = -\nabla\psi_j(\mathbf{r})$, which obeys $\nabla^2\psi_j - \left(\frac{\partial m_{j,x}}{\partial x} + \frac{\partial m_{j,y}}{\partial y}\right) = 0$

three independent variables

$$m_{j,x}(\mathbf{r}) = m_{j,x}(x)\, e^{i\mathbf{q}\cdot\mathbf{s}}$$
$$m_{j,y}(\mathbf{r}) = m_{j,y}(x)\, e^{i\mathbf{q}\cdot\mathbf{s}}$$
$$\psi_j(\mathbf{r}) = \psi_j(x)\, e^{i\mathbf{q}\cdot\mathbf{s}}$$

where $\mathbf{q} = (q_y, q_z)$, and $\mathbf{s} = (y, z)$

Bulk dynamics

Solutions

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

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

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

wave vectors

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

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

where $f_j = \omega/\omega_{\mathrm{M},j}$, and $\eta_j = H_0/M_{\mathrm{s}j}$.

Bulk dynamics

we reduce number of variables using

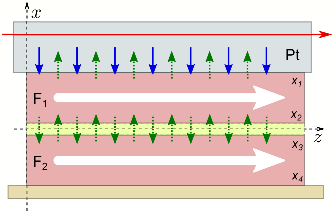
$$C_{j,n}^{(l)} = p_{j,n}^{(l)} C_{j,1}^{(l)} + q_{j,n}^{(l)} D_{j,1}^{(l)}$$
$$D_{j,n}^{(l)} = -q_{j,n}^{(l)} C_{j,1}^{(l)} + p_{j,n}^{(l)} D_{j,1}^{(l)}$$

12 independent variables

$C_{j,1}^{(l)}$ and $D_{j,1}^{(l)}$ for $l = 1,2,3$ and $j = 1,2$.

Boundary conditions

4 interfaces



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

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

$$\mathbf{H}_{\mathrm{eff}\,i1} = H_0\hat{e}_z + \mathbf{h}_1(\mathbf{r},t) + \frac{2A_1}{\mu_0 M_{\mathrm{s}1}^2}\nabla^2\mathbf{M}_1 - \frac{2K^{\mathrm{s}}{}_1}{\mu_0 M_{\mathrm{s}1}^2\delta}(\mathbf{M}_1 \times \hat{n}_1)\hat{n}_1$$

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 ($x = x_{i1}$)

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

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

where $G_1 = \hbar\, g_{r1}^{(e)}/(8\pi)$ with $g_{r1}^{(e)}$ being mixing conductance of the top interface

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

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

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

where $G_2 = \hbar\, g_{r2}/(8\pi)$ with $g_{r2}^{(e)}$ being mixing conductance of the bottom interface

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

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

$$\left(\sigma\frac{A_1}{M_{s1}}\frac{\partial}{\partial x}-\frac{-\sigma K^{\mathrm{i}}{}_1+A_{12}}{M_{s1}}+i\,\sigma\frac{G_{12}}{M_{s1}}\,\omega\right)m_{1,x}\,|_{x_{i2}}+\left(\sigma\frac{A_{12}}{M_{s2}}-i\,\frac{G_{12}}{M_{s1}}\omega\right)m_{2,x}\,|_{x_{i3}}=0$$

Second couple

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

$$\left(\frac{A_2}{M_{s2}}\frac{\partial}{\partial x}+\frac{-K^{\mathrm{i}}{}_2+\sigma A_{12}}{M_{s2}}-i\,\frac{G_{12}}{M_{s2}}\,\omega\right)m_{2,x}\,|_{x_{i3}}-\left(\frac{A_{12}}{M_{s1}}-i\,\sigma\frac{G_{12}}{M_{s2}}\omega\right)m_{1,x}\,|_{x_{i2}}=0$$

where A_{12} is static (RKKY) interlayer coupling, and

$G_{12}=\hbar\,g_{\mathrm{r}}{}^{(i)}/(8\pi)$ with $g_{\mathrm{r}}{}^{(i)}$ being mixing conductance of the spacer

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 $D_{j,1}^{(l)}$.
- The system of linear equation has nontrivial solution when

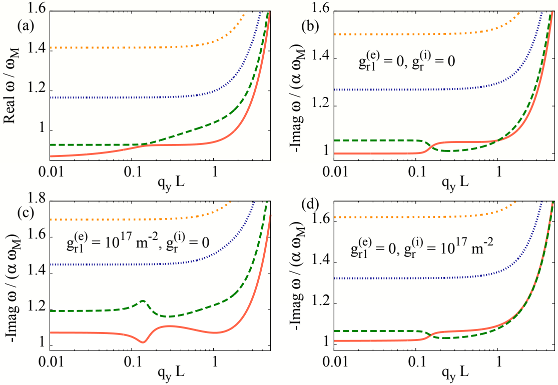
$$\det \bar{\mathbf{M}} = 0$$

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

- we find numerically $\omega = \omega_{\rm r} + i\,\omega_{\rm i}$ satisfying the condition.

No interface anisotropy

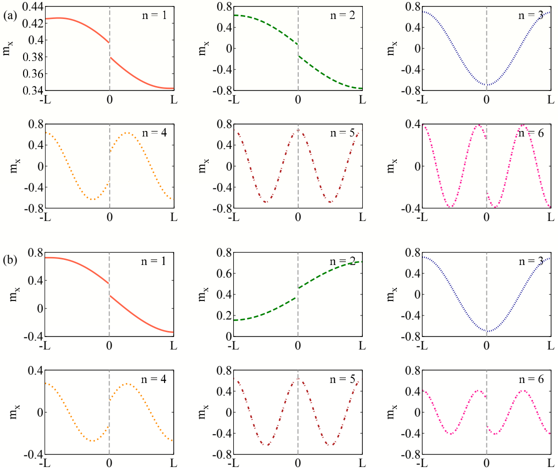
Spin wave spectra



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

No interface anisotropy

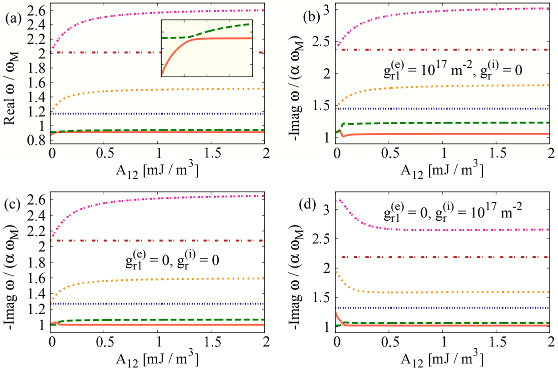
Spin wave profiles



(a) $qL = 0.1$, (b) $qL = 0.3$

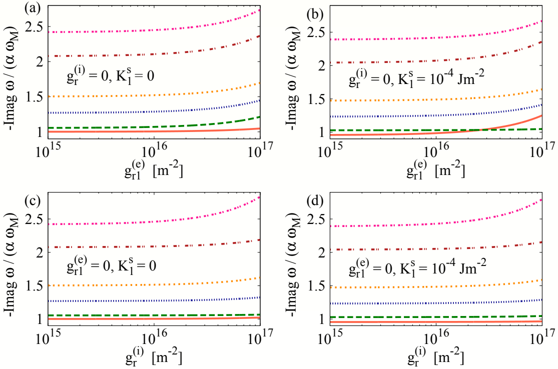
No interface anisotropy

Dependence on interlayer coupling A_{12}



(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



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

Summary

- Tunability of critical current in a spin valve with composite free layer with AF exchange coupling has been studied.
- Manipulation of spin wave damping by means of spin pumping in a YIG double layer has been demonstrated.

Dziękuję bardzo za uwagę