Designing a Spin-Seebeck Diode

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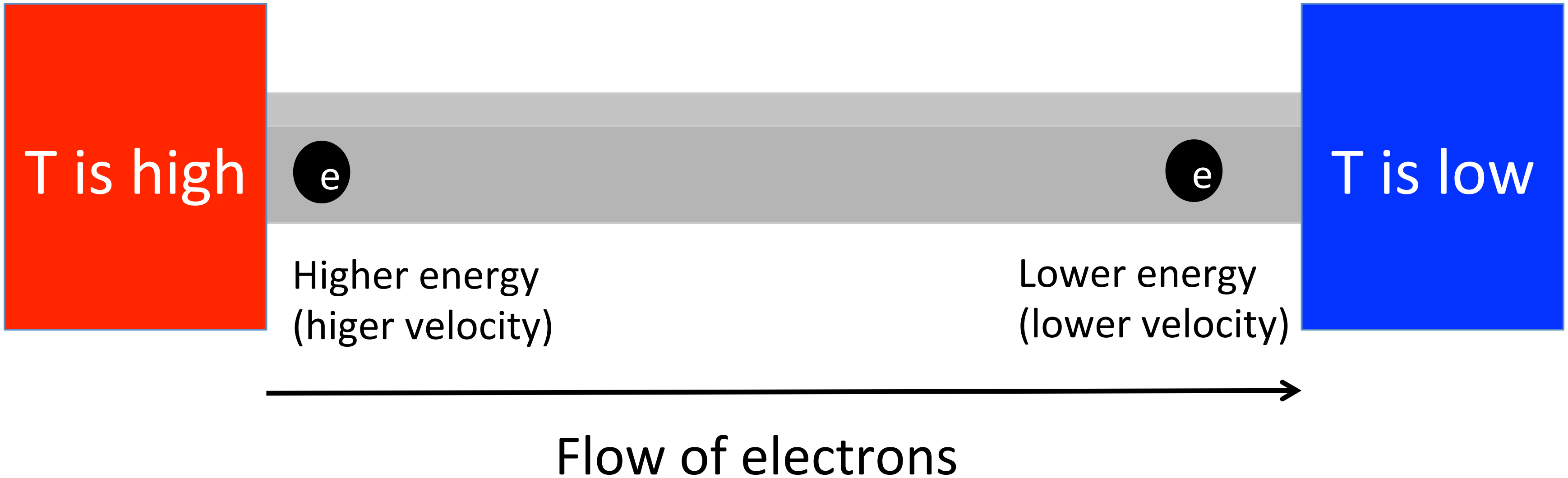
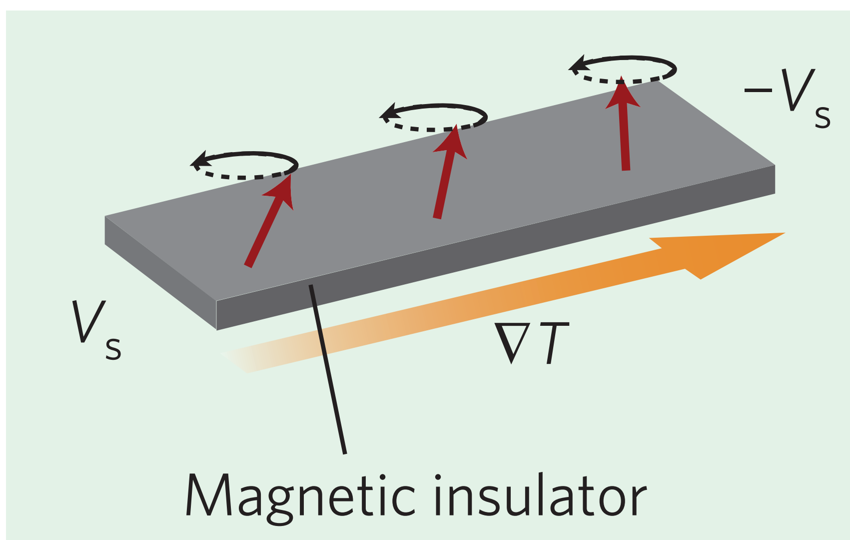
Seebeck effect



$$\mathbf{E} = -S\,\nabla T$$

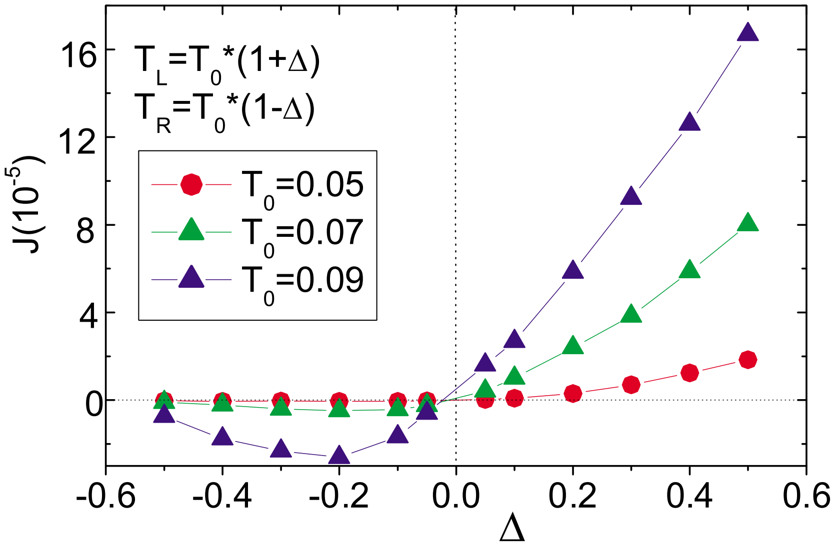
S : Seebeck coefficient



Spin Seebeck effect

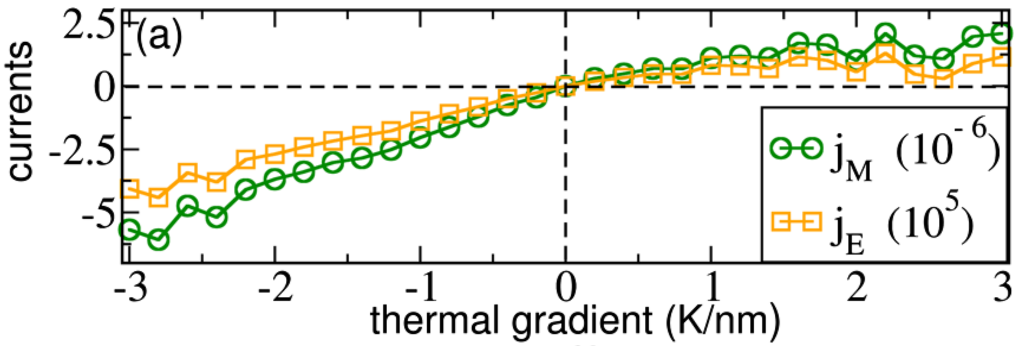
Thermal Diode

Conventional thermal diode



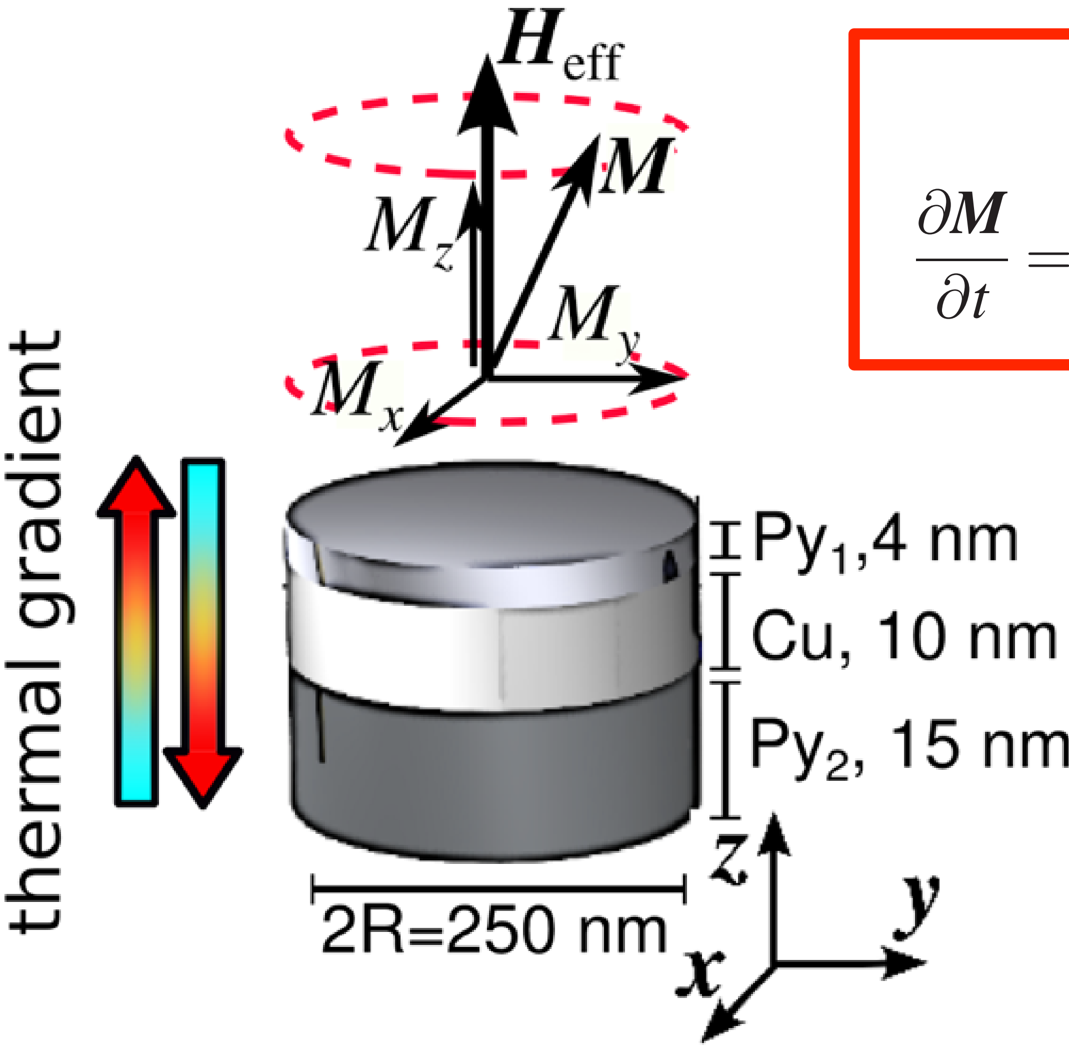
Electron current only for one sign of the temperature gradient

Thermal spin diode



Spin current only for one sign of the temperature gradient

System and Model

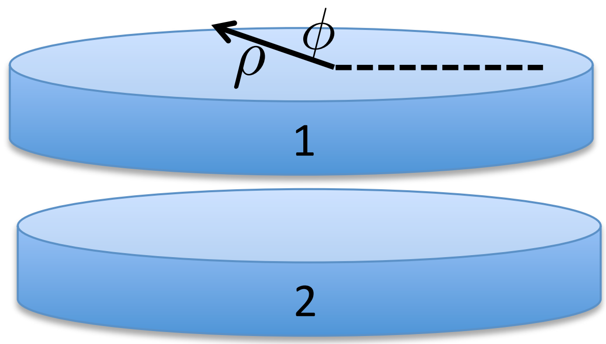


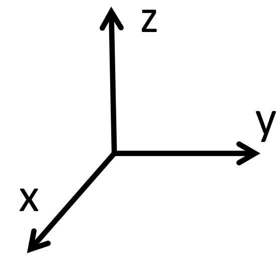
LLG equation

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma_0 \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \frac{\alpha}{M_s} \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t}$$

- external field
- exchange field
- demagnetizing field

System and Model





Thin magnetic disks ⟶ ***M*** is uniform along the thickness

⟶ LLG describe circular precession of M_x and M_y

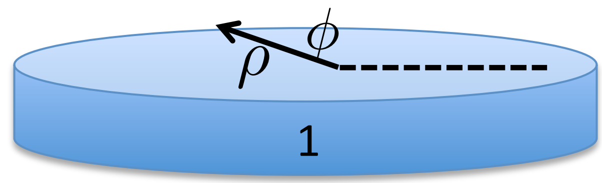
$$c(\rho,\phi,t) = \frac{M_x(\rho,\phi,t) + iM_y(\rho,\phi,t)}{\sqrt{2M_s(M_s+M_z)}} \qquad p_j = |c_j|^2$$

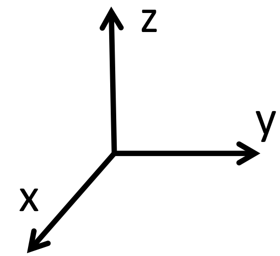
Resonance frequency Damping Dipolar coupling

LLG equations

$$\begin{cases} \dot{c}_1 = i\omega_1(p_1)c_1 - \Gamma_1(p_1)c_1 + ih_{12}c_2, \\ \dot{c}_2 = i\omega_2(p_2)c_2 - \Gamma_j(p_2)c_2 + ih_{21}c_1 \end{cases}$$

System and Model

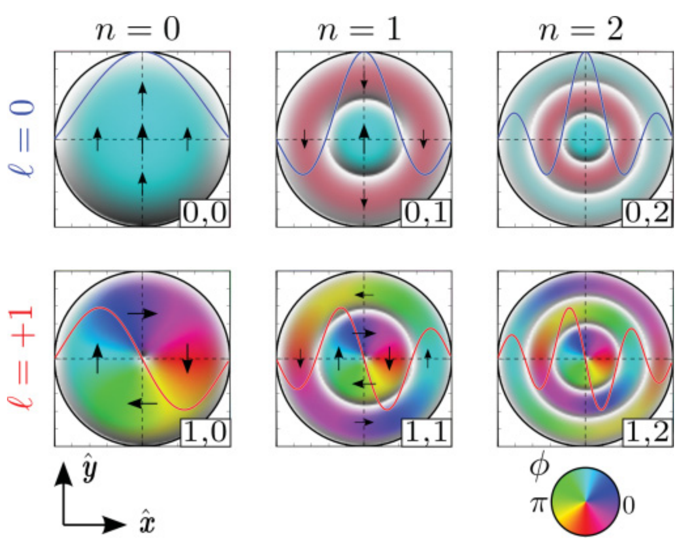




Spin wave modes $c_{\ell,n}(\rho,\phi,t) = J_\ell(k_{l,n}\rho)e^{i\ell\phi}e^{i\omega_{\ell,n}t}$

Bessel Function of the first kind   Spin wave vector

n: radial quantum number

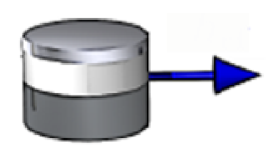


From PRB 84, 224423 (2011)

ℓ: azimuthal quantum number

$\ell = 0$: is excited by uniform in-plane field

in plane rf field



$\ell = 1$: is excited by orthoradial field

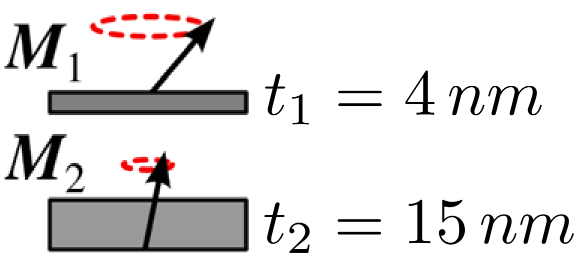
orthoradial rf field

System and Model

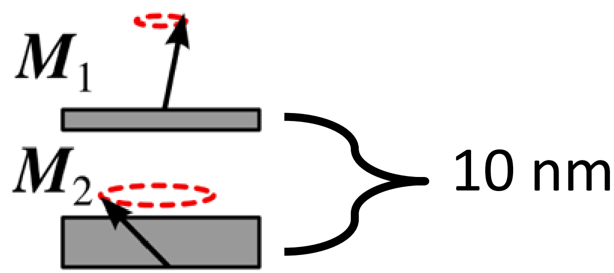
Two disks that **are dipolarly coupled**

→ Spin wave modes decompose into two categories

symmetric modes



asymmetric modes



Use micromagnetic simulation in order to investigate the physics of the coupled disks **(Nmag)**

$R = 125\,nm \quad A = 1.3 \times 10^{-11} J/m \qquad \alpha_1 = 1.6 \times 10^{-2} \quad 0.85 \times 10^{-2}$

$M_{s1} = 7.8 \times 10^5\,A/m \quad M_{s2} = 9.4 \times 10^5\,A/m \quad \gamma_0 = 1.87 \times 10^{11}\mathrm{rad}^{-1}T^{-1}$

System and Model

Thermal fluctuations are added by introducing a (Gaussian) stochastic field $\boldsymbol{H}_{\mathrm{eff}}^{k}$ at each site *k*,

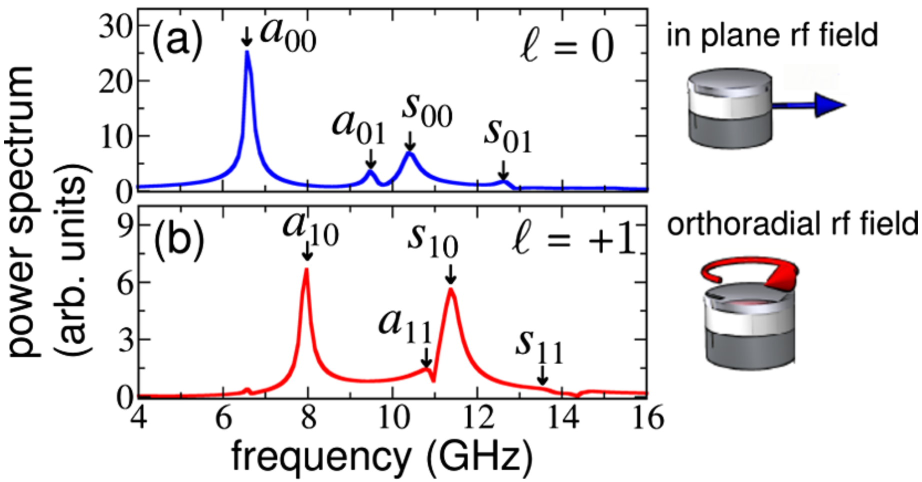
$$\langle \boldsymbol{H}_{\mathrm{th},i}^{k} \boldsymbol{H}_{\mathrm{th},j}^{l} \rangle = 2D_k \delta_{ij} \delta_{kl} \delta(t - t') \qquad i, j = x, y, z$$

$$D_k = (2\alpha k_B T_k)/(M_s \gamma_0 \mu_0 V_k)$$

The quantity of interest in the micromagnetic simulation is the averaged magnetization

$$\langle \mathbf{M}_j(t) \rangle = \frac{1}{V_j} \int_{V_j} \mathbf{M}_j(\mathbf{r}, t)$$

Modes of two coupled disks

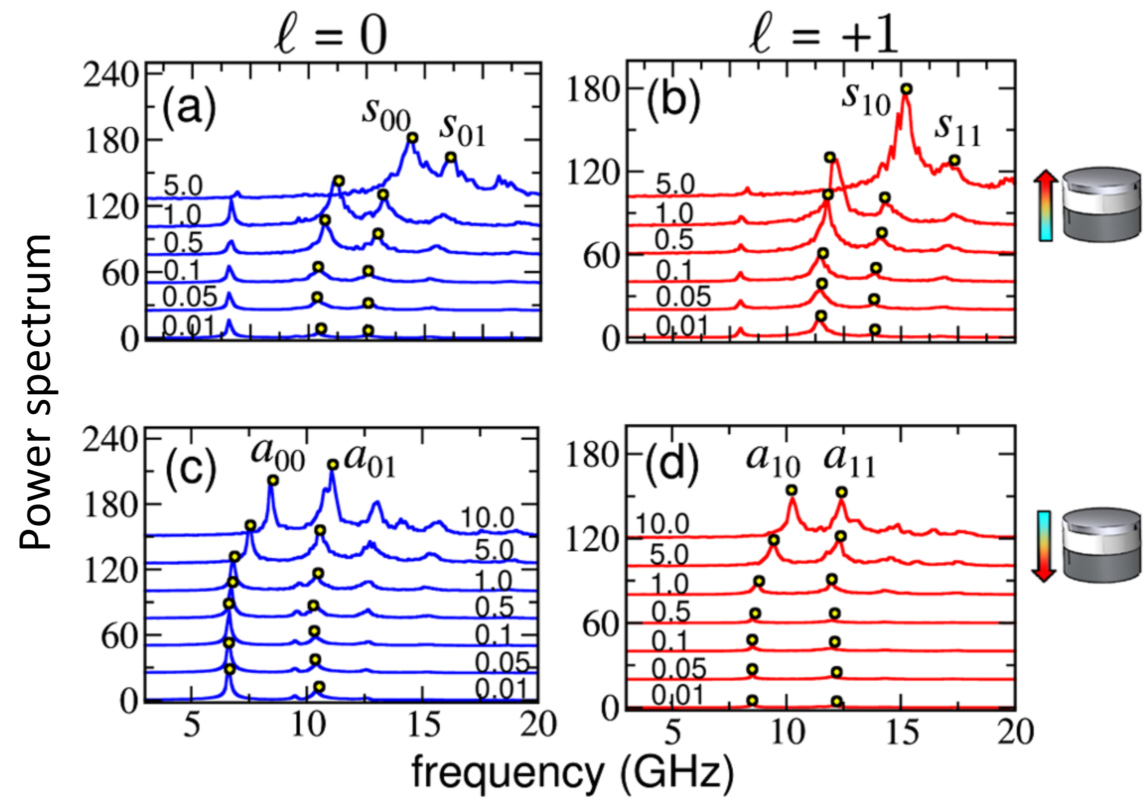


$\ell = 0$ modes	$a_{0,0}$	$a_{0,1}$	$s_{0,0}$	$s_{0,1}$
freq. (GHz)	6.43	9.42	10.35	12.60

$\ell = +1$ modes	$a_{1,0}$	$a_{1,1}$	$s_{1,0}$	$s_{1,1}$
freq. (GHz)	7.98	10.81	11.38	13.58

positive temperature gradient

negative temperature gradient



Thermal Spin Diode

Hamiltonian of the problem

$$\mathcal{H} = \omega_1(p_1)p_1 + \omega_2(p_2)p_2 + h(c_1c_2^* + c_1^*c_2),$$

Number of particles is conserved (p_1+p_2)

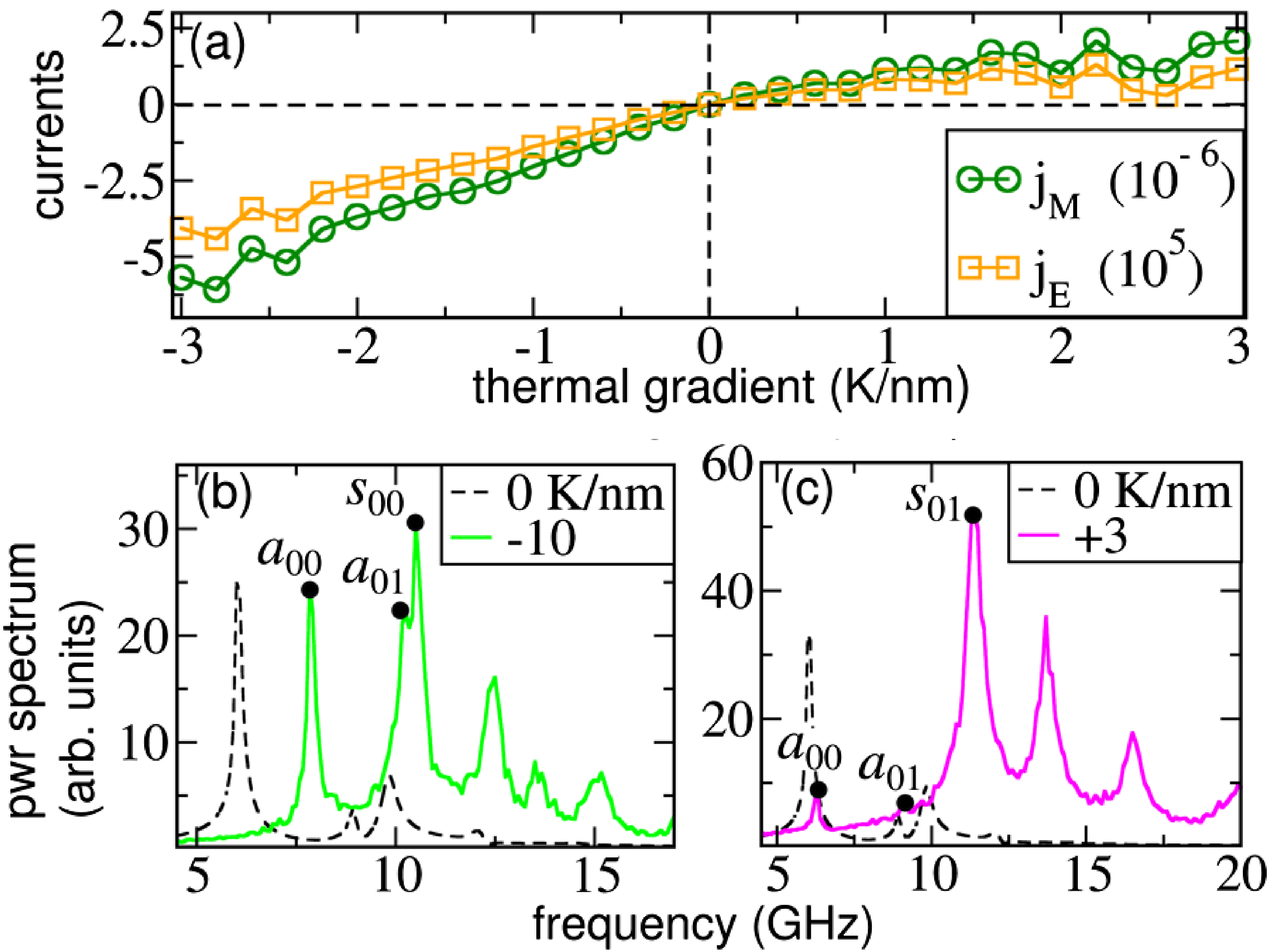
$$\longrightarrow \quad \dot{p}_j = -2\Gamma_j(p_j)p_j + j_{\mathrm{M}}$$

Spin current $$j_{\mathrm{M}} = 2h\,\mathrm{Im}(c_1c_2^*)$$

Similarly energy is conserved

Energy current $$j_{\mathrm{E}} = 2h\,\mathrm{Re}(\dot{c}_1c_2^*)$$

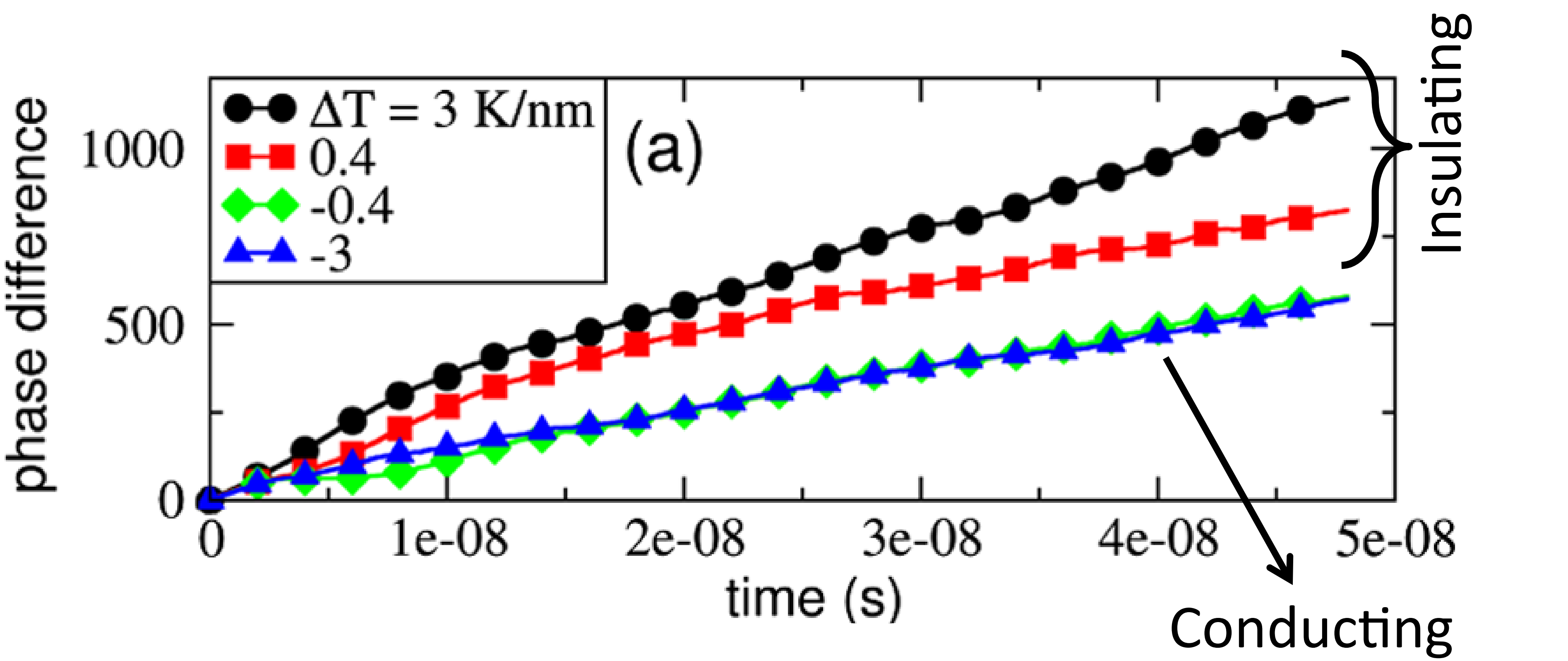
Thermal Spin Diode



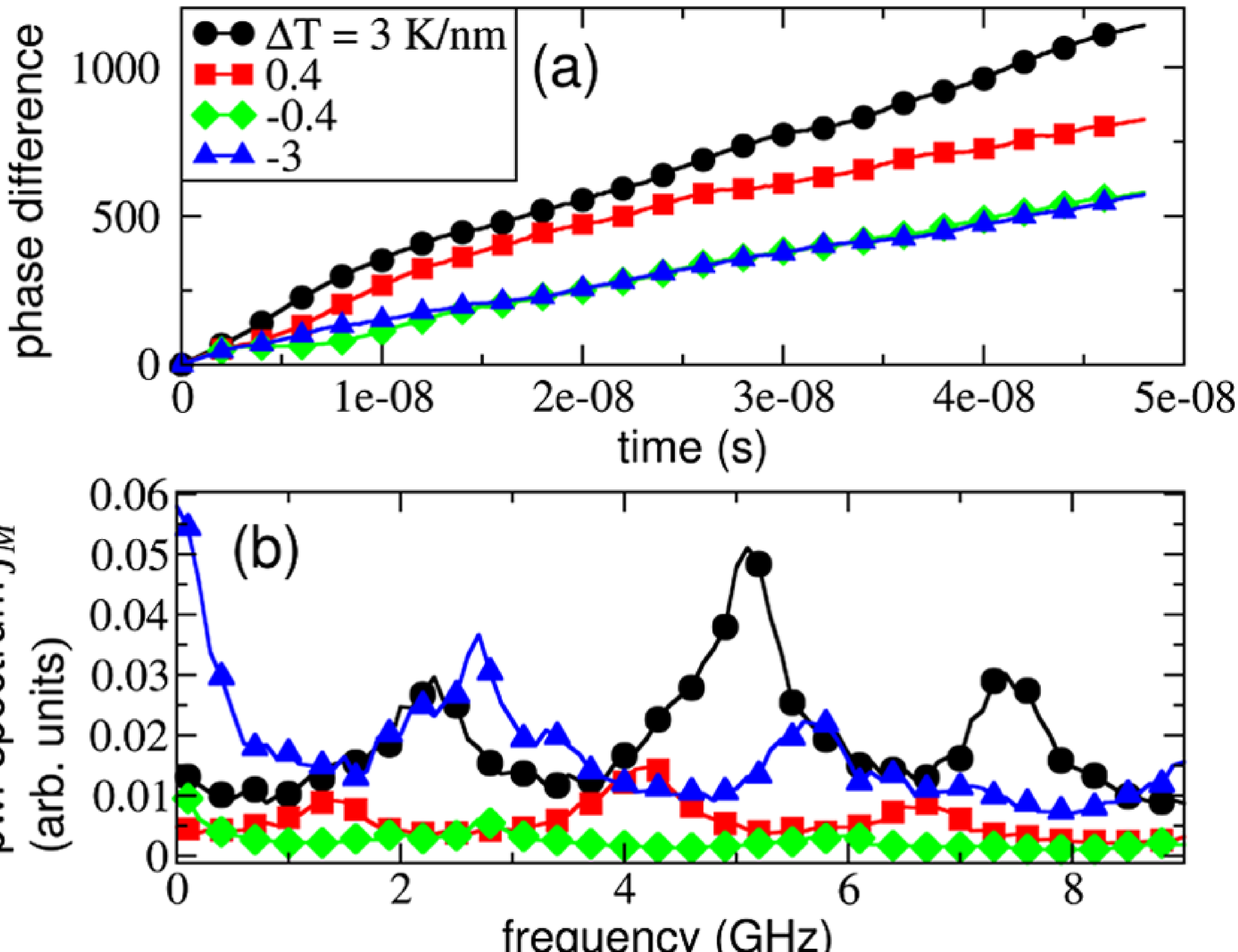
Thermal Spin Diode

$$c_j = \sqrt{p_j} e^{i\phi_j}$$

$$\longrightarrow \; j_M = 2h\sqrt{p_1 p_2}\sin(\phi_1 - \phi_2)$$



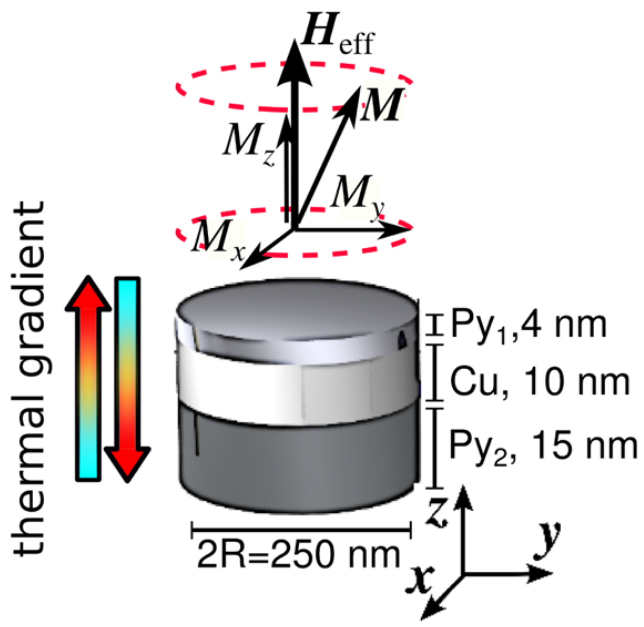
Thermal Spin Diode



Conclusions

- Realistic model for a thermal spin diode

- Might be tested experimentally



THANK YOU !