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Amplification of spin-wave packets through the spin Seebeck effect

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Workshop on Spin Caloritronics
Leiden, May 10, 2011

Motivation for the experiments

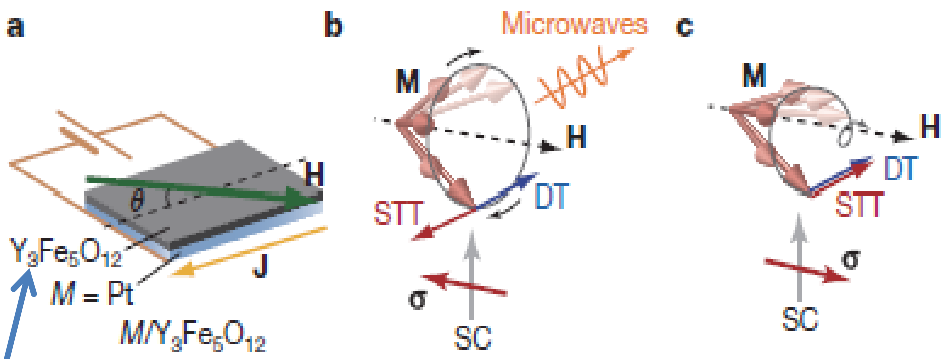
nature

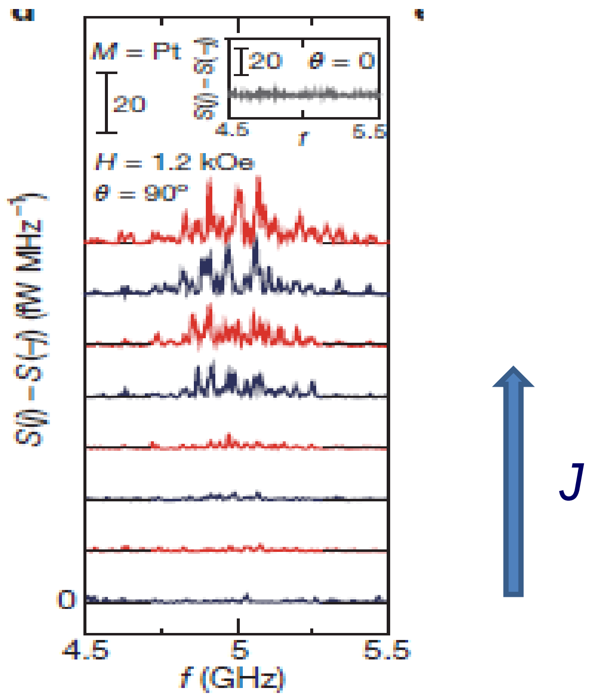
Vol 464|11 March 2010|

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

Y. Kajiwara[1,2], K. Harii[1], S. Takahashi[1,3], J. Ohe[1,3], K. Uchida[1], M. Mizuguchi[1], H. Umezawa[5], H. Kawai[5], K. Ando[1,2], K. Takanashi[1], S. Maekawa[1,3] & E. Saitoh[1,2,4]

Spin Hall effect in Pt creates spin current

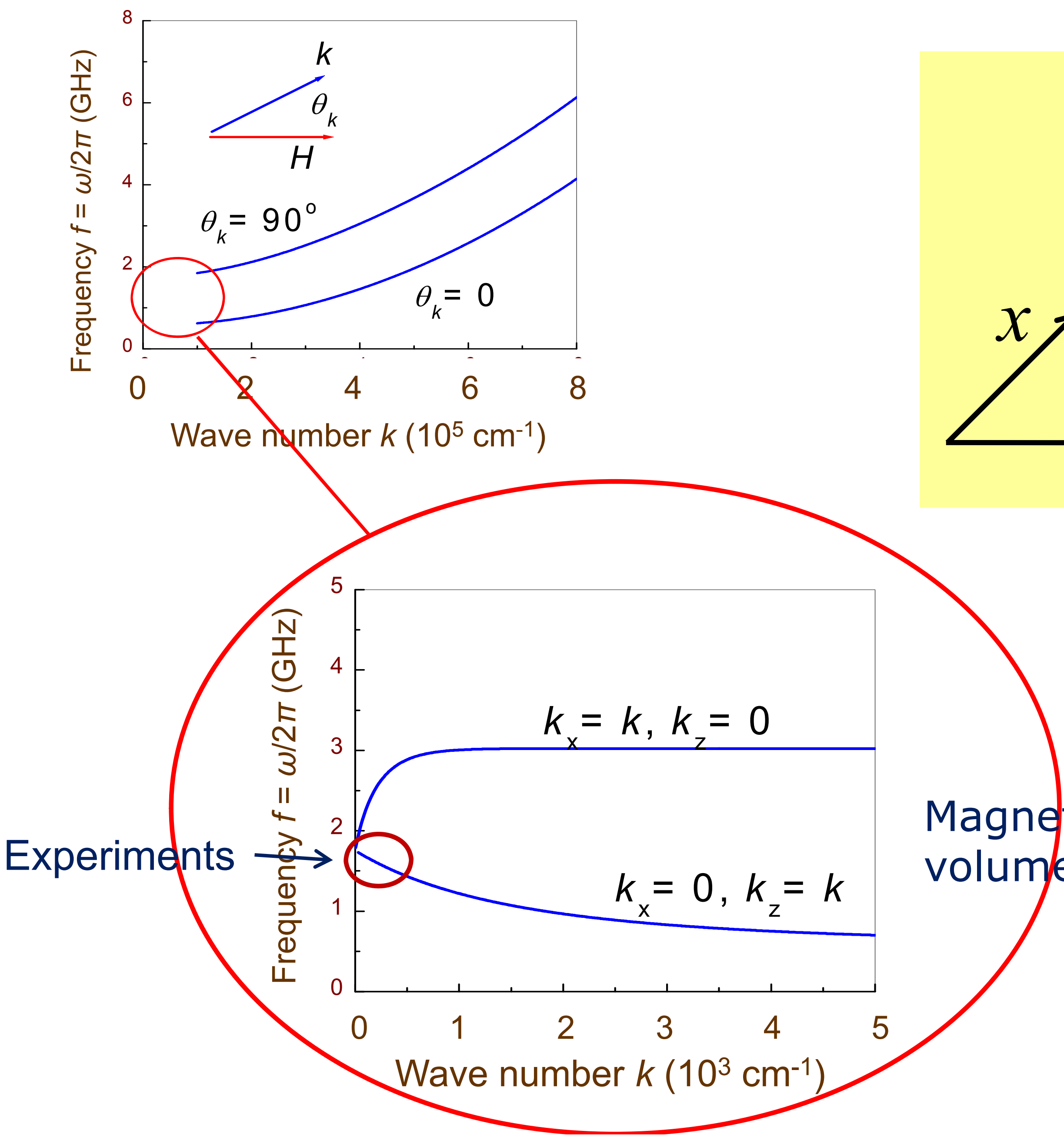


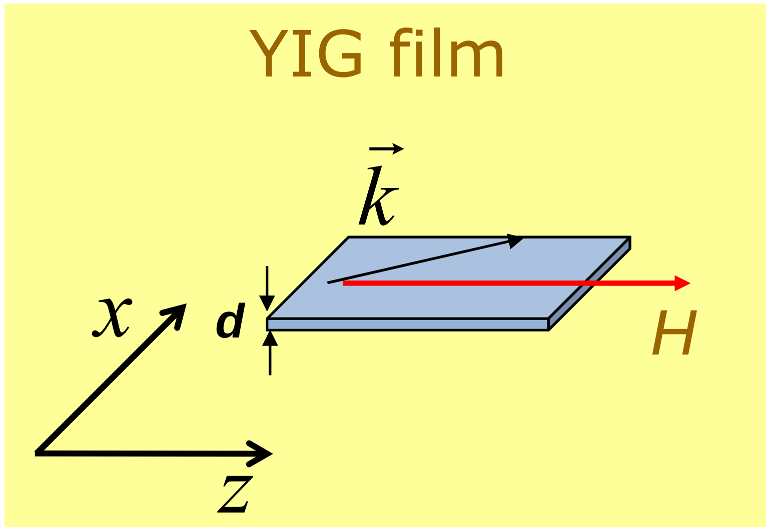


YIG-**Y**ttrium **I**ron **G**arnet is a ferrimagnetic insulator with very small magnetic losses

Excitation of spin waves by the spin-torque due to spin current created through the spin Hall effect

Spin-wave frequency (energy)

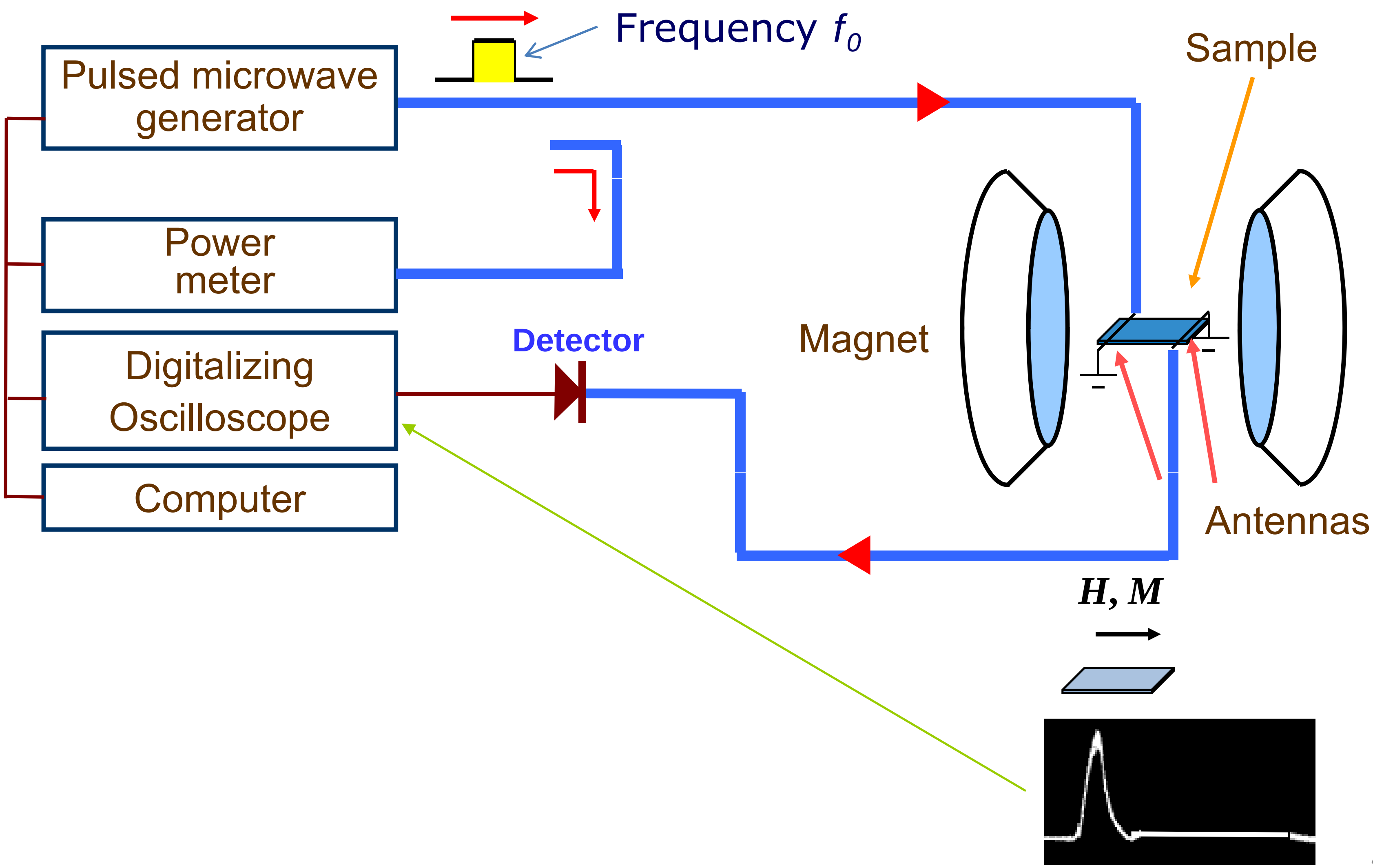




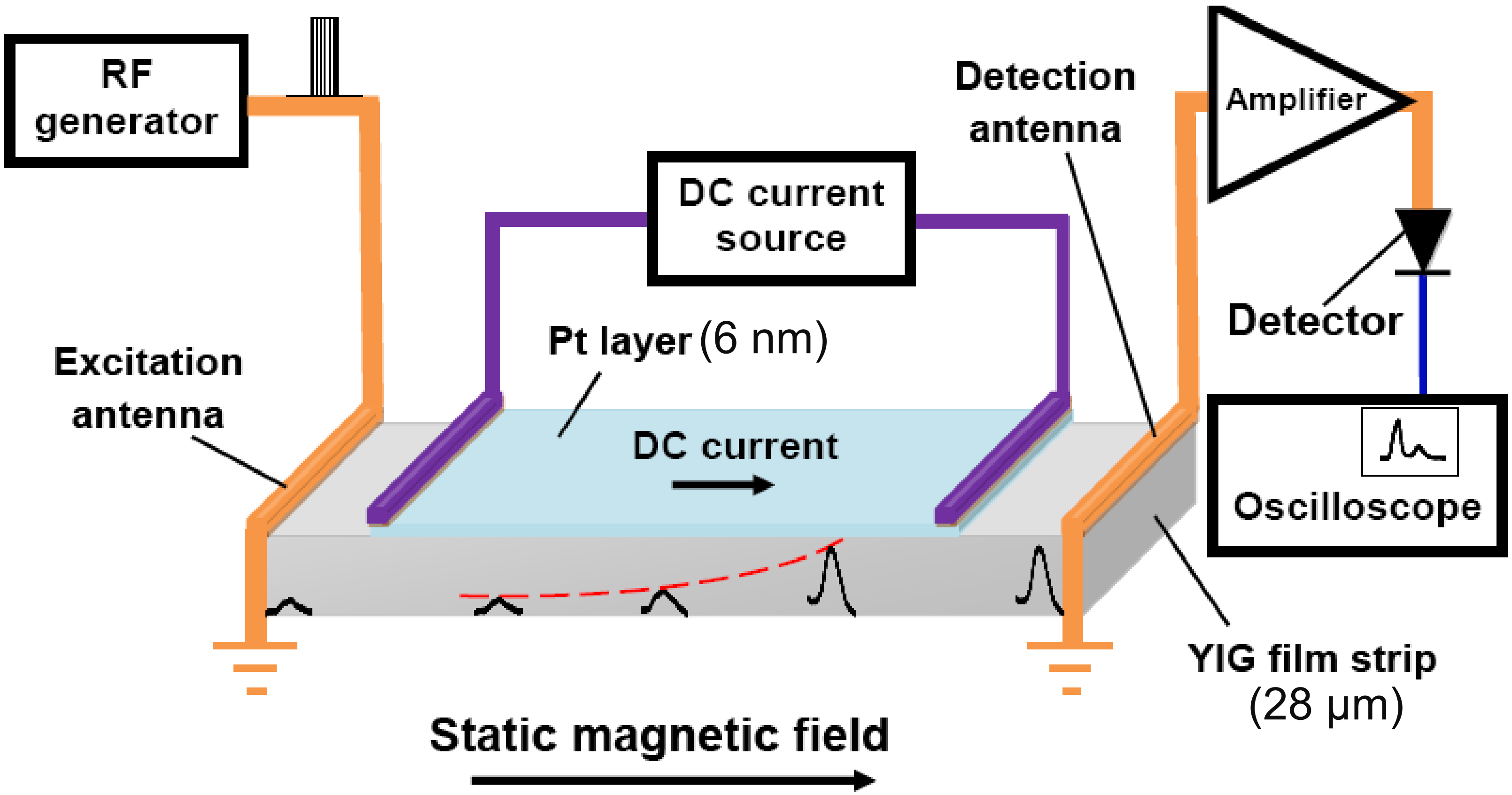
Magnetostatic surface and volume modes

Experiments: Schematics

Excitation of MS spin-wave packets with microwave field

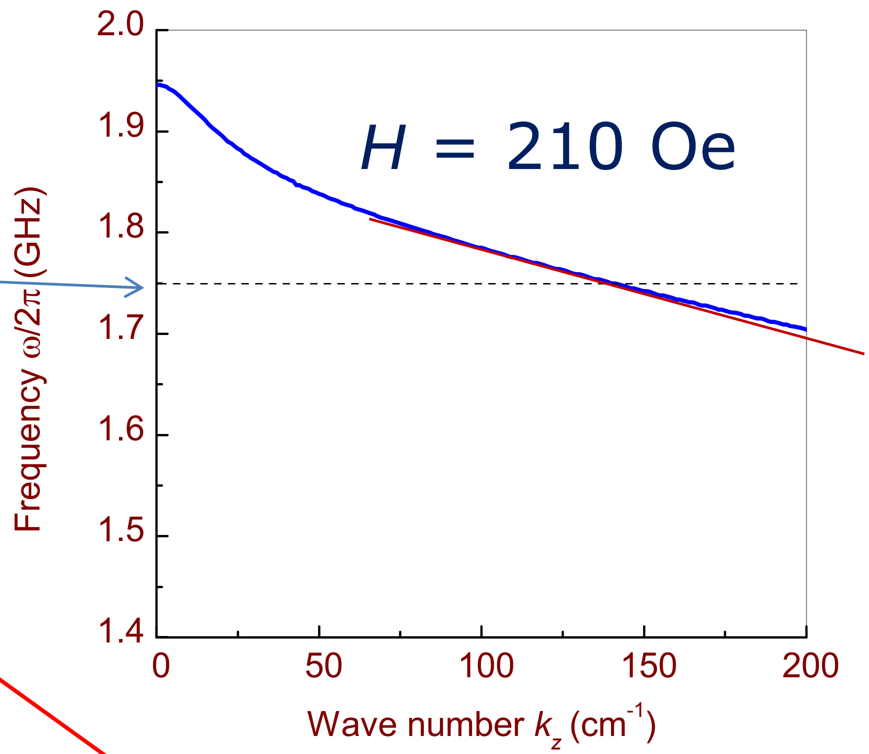


Experiments: Details of sample



Experiments: Propagation of SW packets

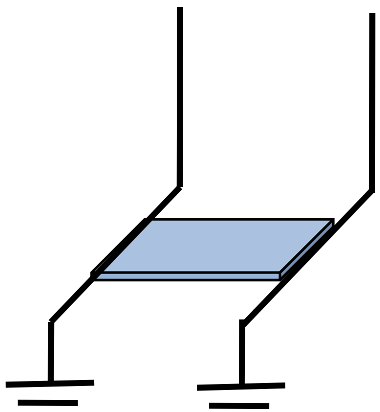
f_0=1.73 GHz

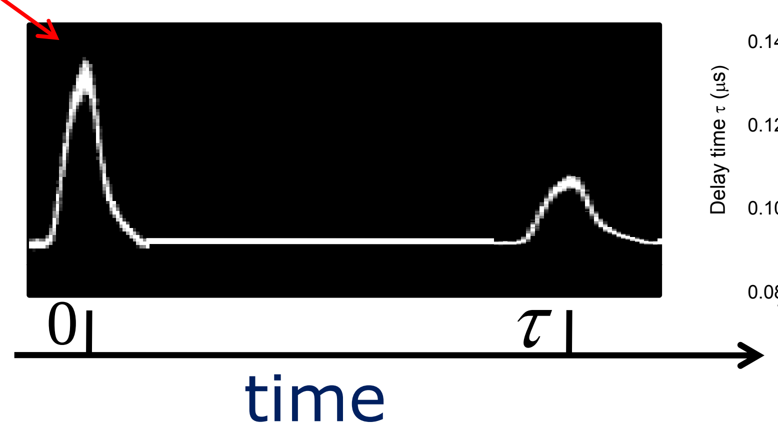


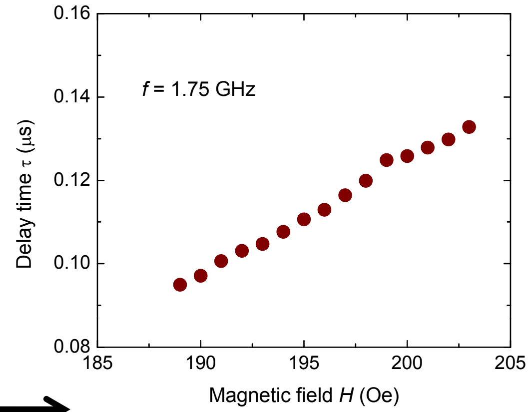
$$v_g = \partial \omega_k / \partial k$$

$$\tau = L_a / v_g$$

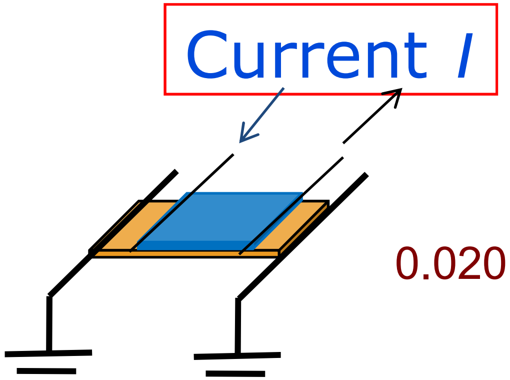
Direct electromagnetic coupling between antennas



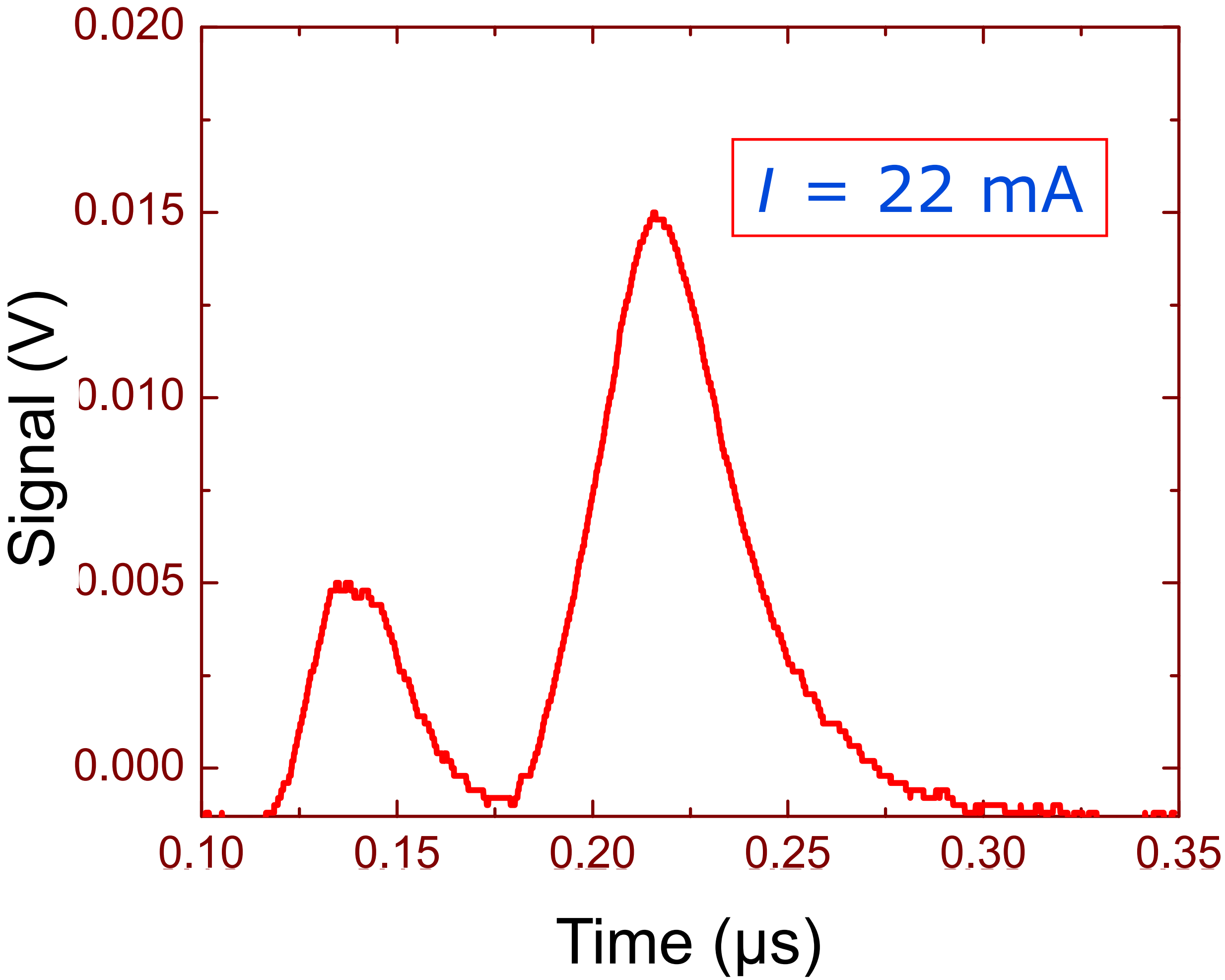


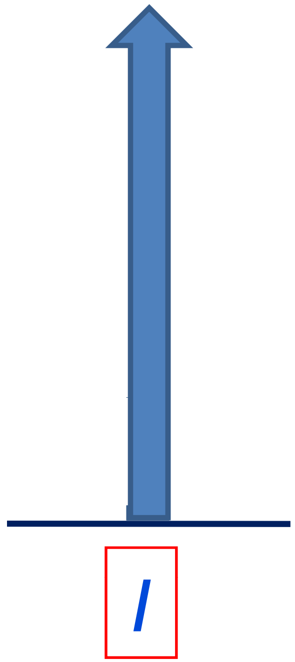


Spin-wave amplification by action of current *I*

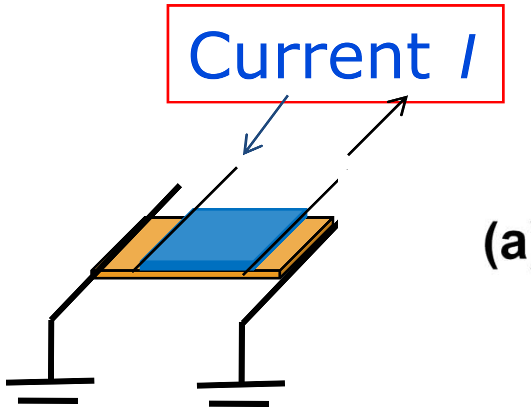


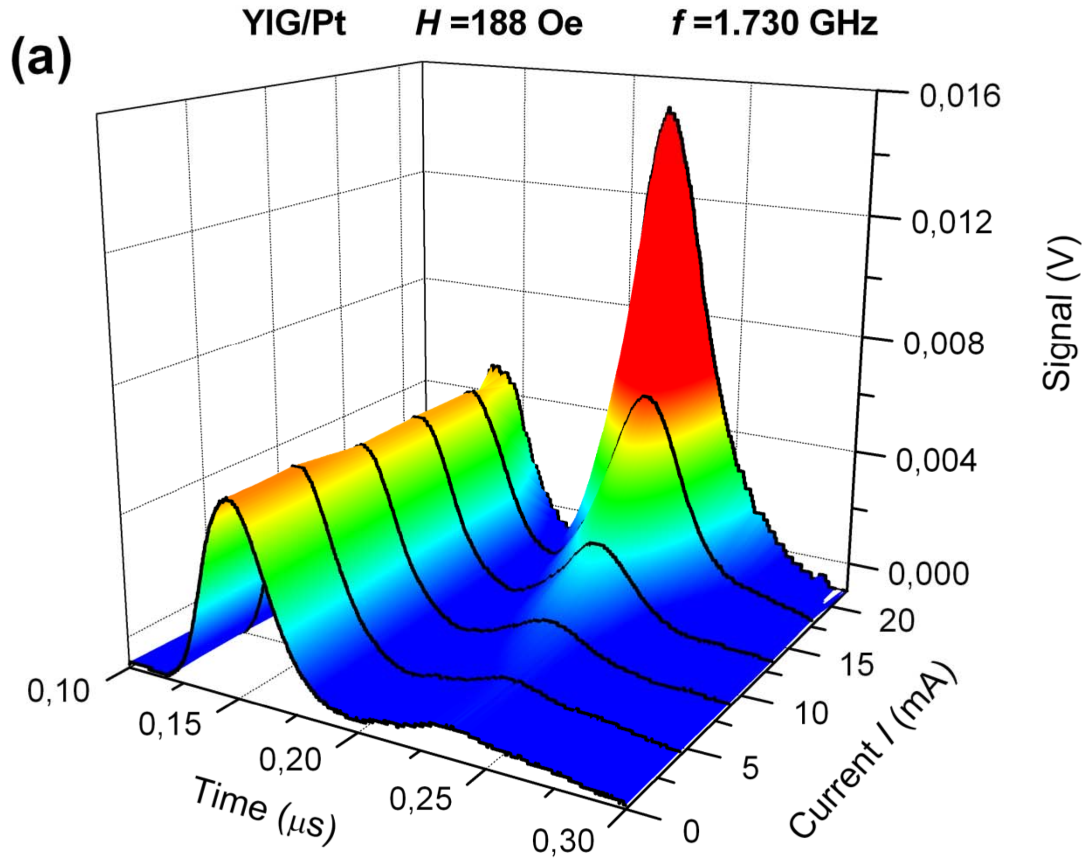
f = 1.73 GHz, H = 188 Oe





Spin-wave amplification by action of current *I*



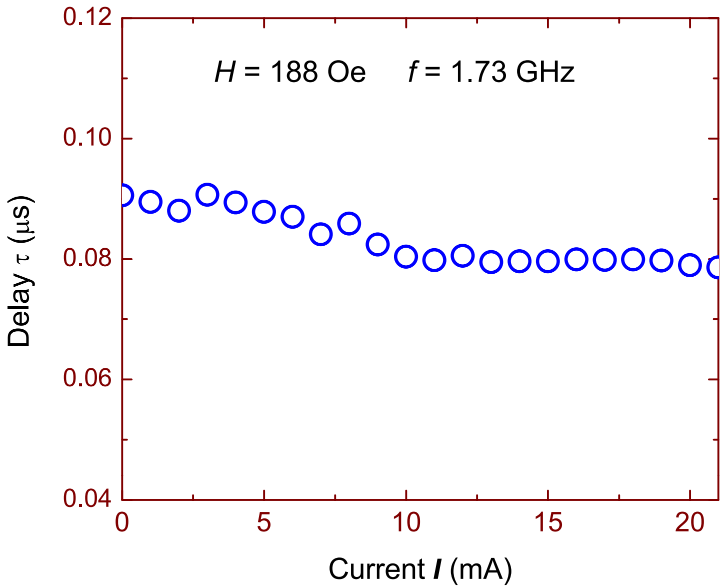


Interpretation

Mechanism of amplification

Spin Hall effect? Spin-torque created by J_S generated by the SHE in the Pt layer

Evidences of heating: 1- Time constant of few seconds
2- Reduction in delay time with current



$$\omega \approx \gamma H_t^{1/2} [H_t + 4\pi M(T)]^{1/2}$$

$$\Delta\tau = a_H (\gamma H / \omega)^2 \Delta(4\pi M)$$

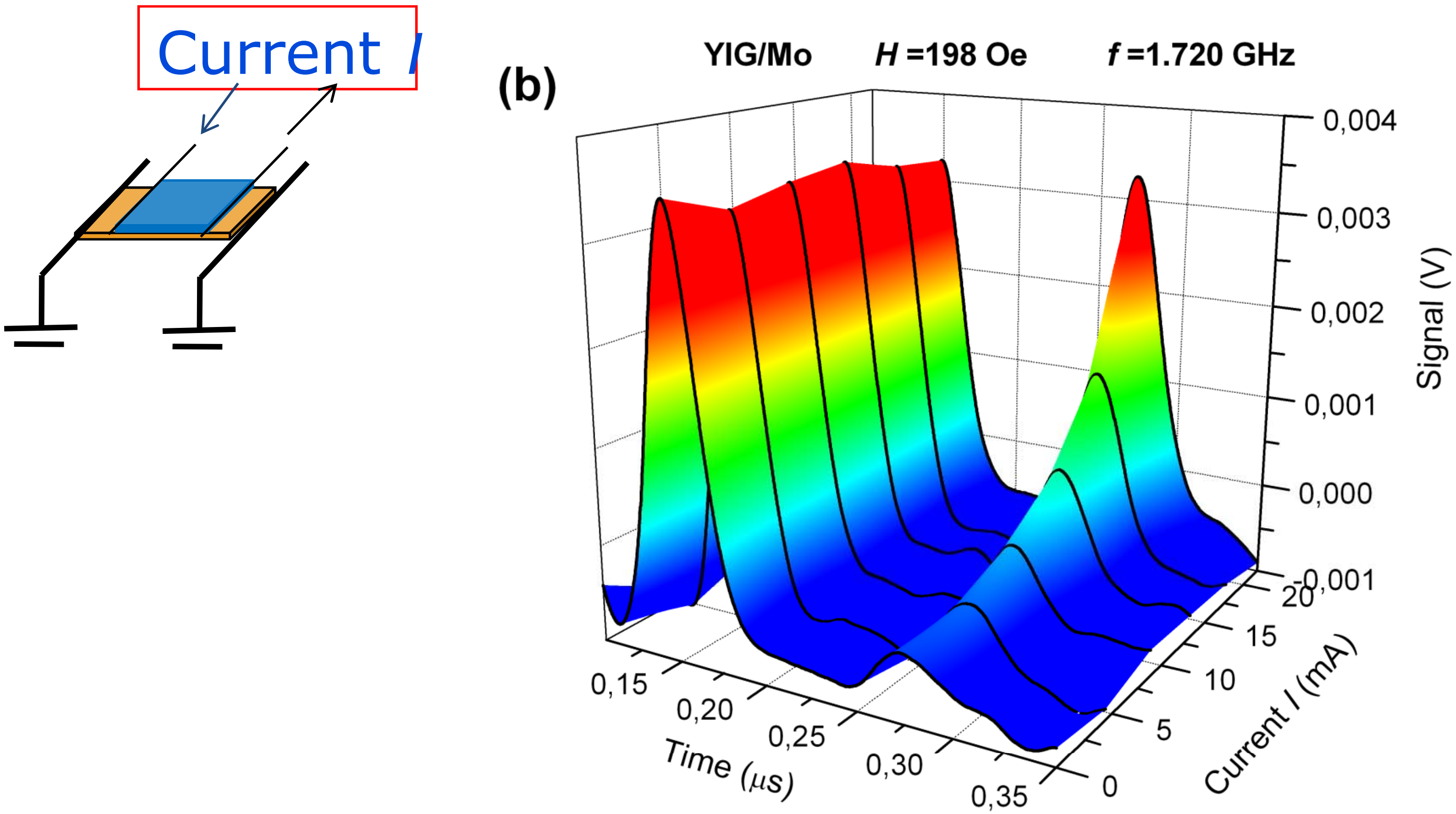
$$a_H = \Delta\tau / \Delta H$$

I = 20 mA

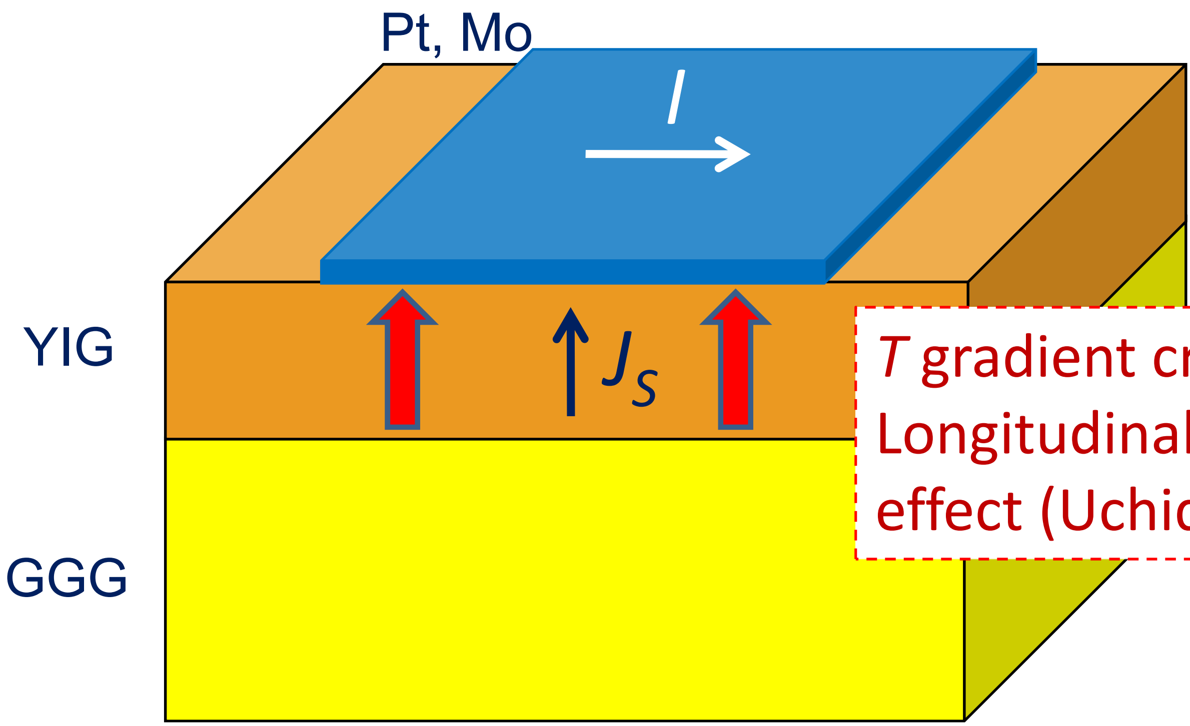
Δ4πM ~ 40 G   ΔT ~10 K

Repeat experiments with YIG/Mo

Mo has Hall angle much smaller than Pt but has comparable resistivity



Spin Seebeck effect? Spin-wave model



T gradient creates J_s
Longitudinal spin Seebeck effect (Uchida et al 2010)

$$J_S = \beta \nabla T \qquad \beta \propto S_s$$ (spin Seebeck coefficient)

$$\vec{\tau} = -J_S \ \vec{S} \times (\vec{\sigma} \times \vec{S})$$

Spin torque due to spin current J_S created by the SSE
Hatami, Zhang, Bauer, Kelly, PRL 2007
Slonczewski, PRB 2010

Model for spin-wave amplification through SSE

Equations of motion for spin waves under spin torque

$$\left(\frac{dc_k}{dt}\right)_{kinetic} = \frac{1}{i\hbar}[c_k, H^{(2)}] = -i\omega_k c_k$$ + STT + relaxation

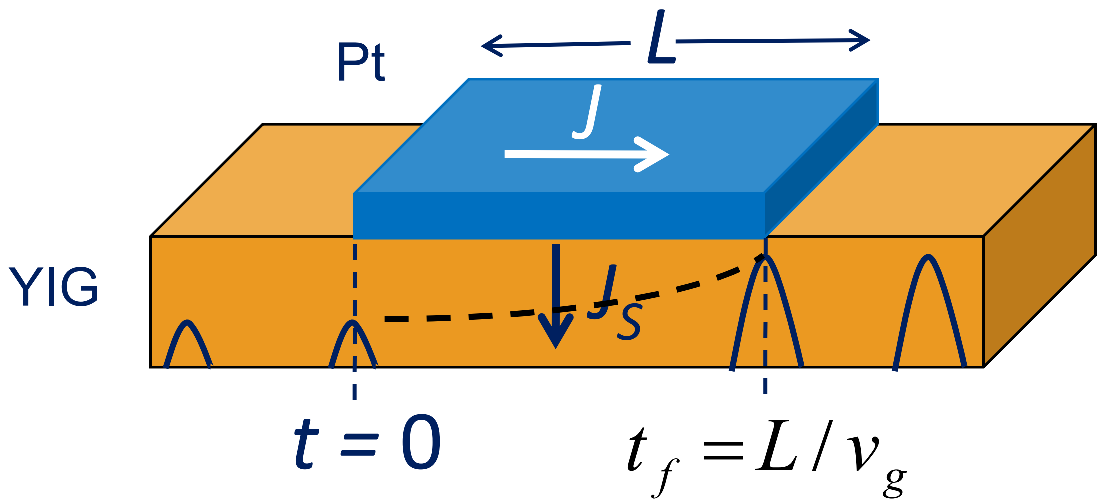
For $n_k << NS$ $\Longrightarrow$ $$\frac{dc_k}{dt} = -i\omega_k c_k - (\eta_k - \beta \nabla T) c_k$$

Relaxation rate

Spin torque

$$\boxed{c_k(t) = c_k(0)\, e^{-i\omega t} \;\; e^{-(\eta_k - \beta \nabla T)t}}$$

Spin-wave amplification through SSE



$$\boxed{c_k(t) = c_k(0)\, e^{-i\omega t} \; e^{-(\eta_k - \beta \nabla T) t_f}}$$

Amplification gain

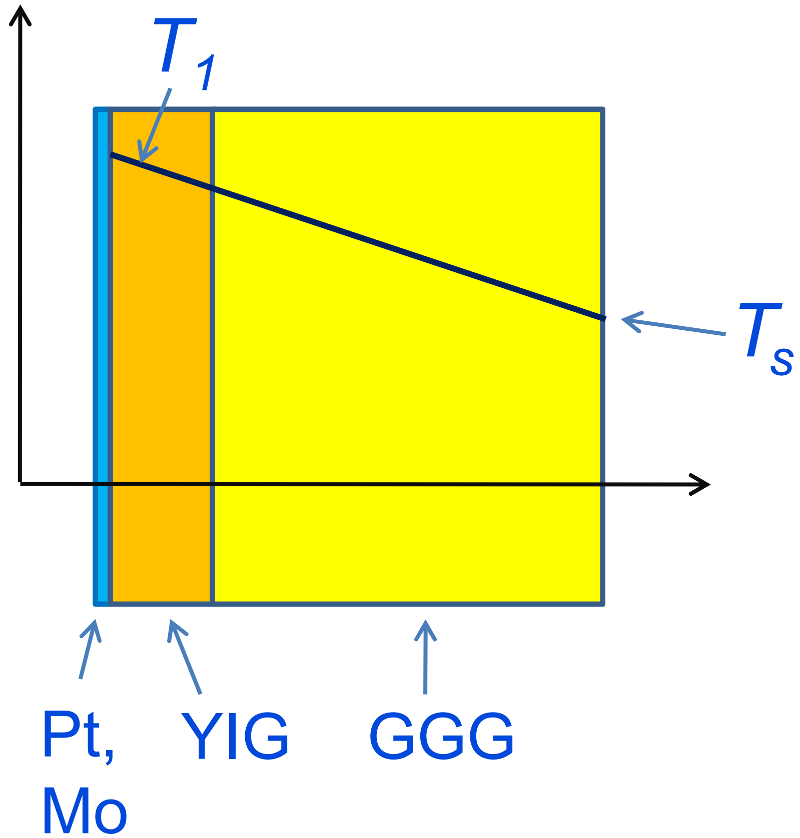
Critical T gradient

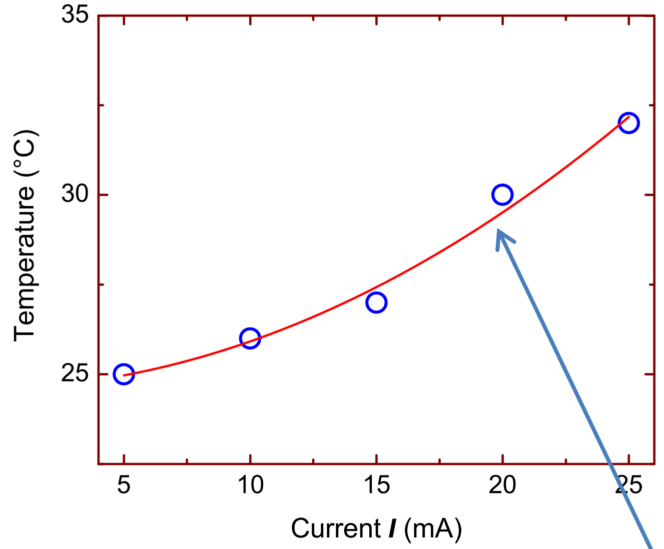
$$\nabla T_c = \eta_k / \beta$$

$$\nabla T \geq \nabla T_c \quad \boxed{G(\nabla T) = \left| \frac{c_k(t_f, \nabla T)}{c_k(t_f, \nabla T_c)} \right|^2 = e^{a(\nabla T / \nabla T_c - 1)}}$$

$$a = 2\eta_k L / v_g$$

Temperature gradient





$$T_s = c_1 I + c_2 I^2$$

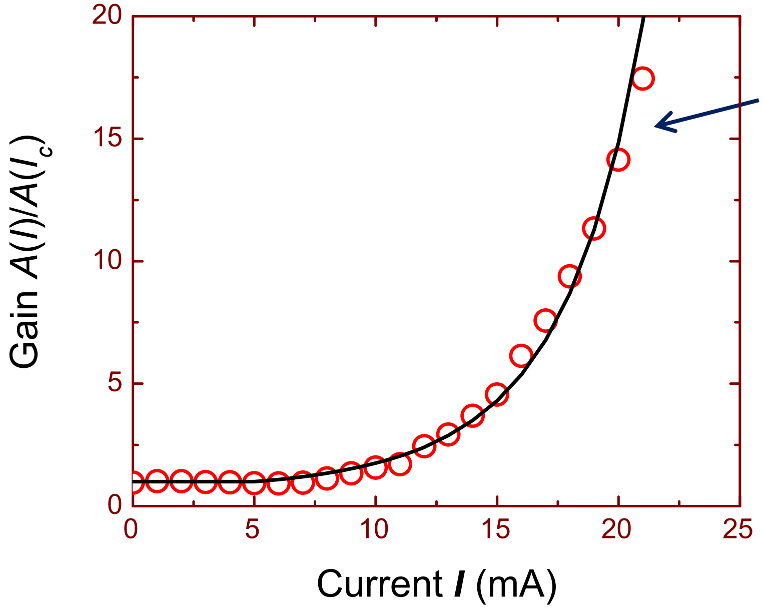
$$c_2 / c_1 = 0.6$$

$$\nabla T = b_1 I + b_2 I^2$$

Critical heating current $\beta (b_1 I_c + b_2 I_c^2) = \eta_k$

Spin-wave amplification through SSE

YIG/Pt H = 188 Oe f = 1.73 GHz



Theory $G(I/I_c) = \exp\left[a\left(\frac{b_1 I + b_2 I^2}{b_1 I_c + b_2 I_c^2} - 1 \right) \right]$

b_2/b_1=0.6 (fixed)

Fit gives $a = 2\eta_k L / v_g$ = 0.23 I_c = 5 mA

With v_g = 1.2 x 10^7 cm/s obtained from the measured delay time find

$$\eta_k = 3.5 \times 10^6\ \mathrm{s}^{-1}$$

Gilbert damping

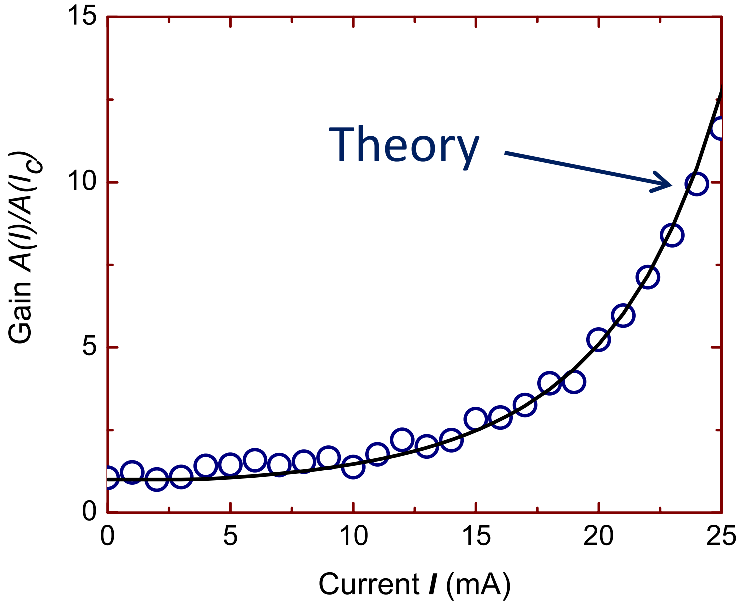
$$\alpha = \eta_k / \omega = 3 \times 10^{-4}$$

Linewidth

$$\Delta H = \eta_k / \gamma = 0.2\ \mathrm{Oe}$$

Spin-wave amplification through SSE

YIG/Mo H = 198 Oe f = 1.72 GHz



Ic = 3.5 mA, a = 0.07

η_k = 0.75 x 10^6 s^{-1}

Gilbert damping

$\alpha = \eta_k / \omega$ = 7 x 10^{-5}

Smaller damping in YIG/Mo expected because **spin pumping damping** in Mo is much smaller than in Pt

Conclusion: Spin-wave model with STT from LSSE explains amplification

Many thanks for your attention