Spin-Hall nano-oscillators

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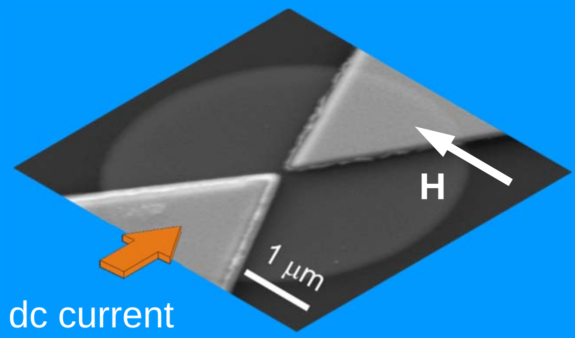

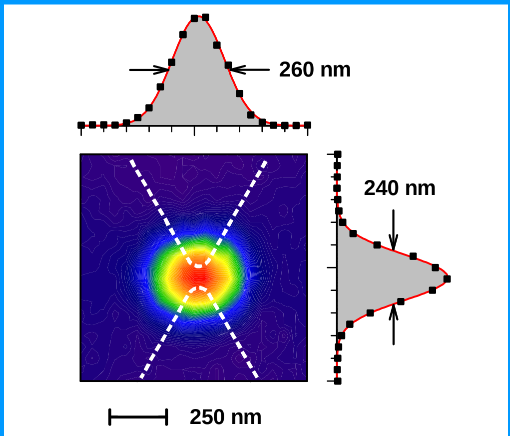

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Group of NonLinear Magnetic Dynamics

Motivation

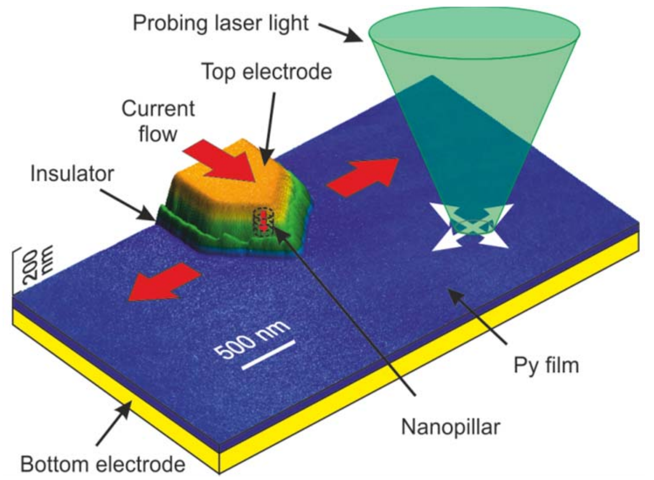
1. Spin transfer torque (STT) phenomena allow the control of the magnetization dynamics by using spin-polarized electric currents.
2. Usually STT spin current is accompanied by a charge current (spin-polarized electric current).
3. STT can be produced by pure spin currents generated due to, e.g., the spin Hall effect (SHE).

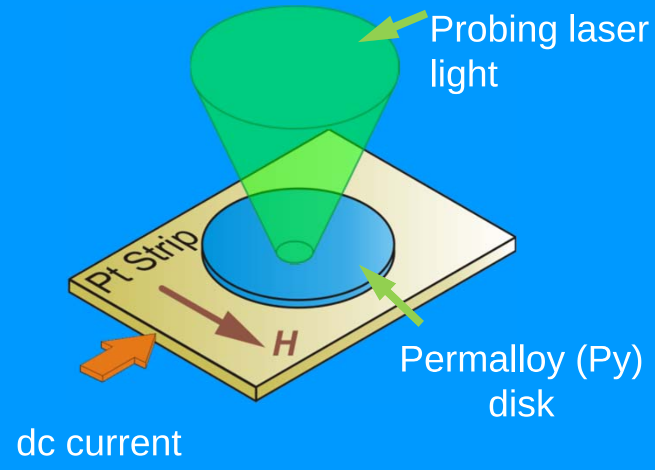
Advantages in comparison with spin-polarized current:

(i) Charge current does not flow through the ferromagnet, which makes the devices more stable against heating and electromigration, as well as enables the use of dielectric magnetic materials.

(ii) SHE devices enable direct optical access to the active area, providing unique possibilities for new insights into the physics of STT phenomena.

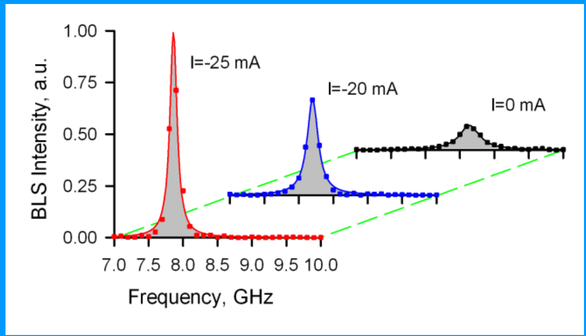
(iii) Effectiveness in terms of $\hbar/e$



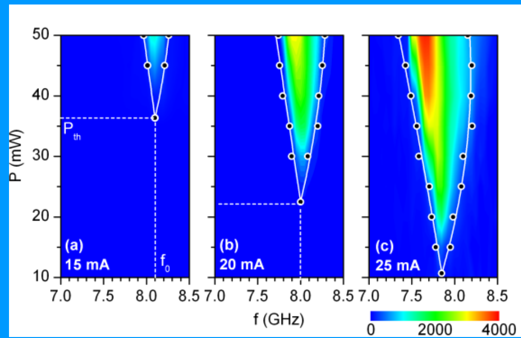


Outline

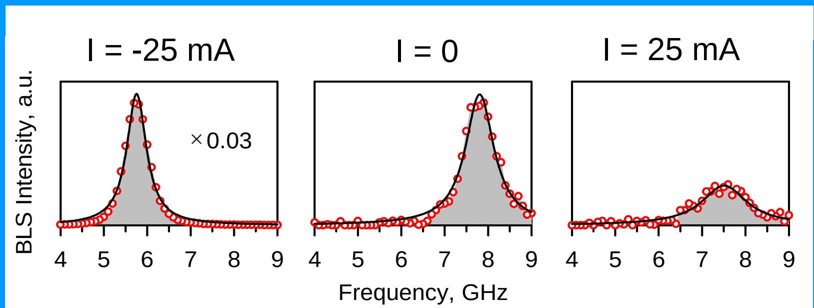
Control of effective FMR linewidth



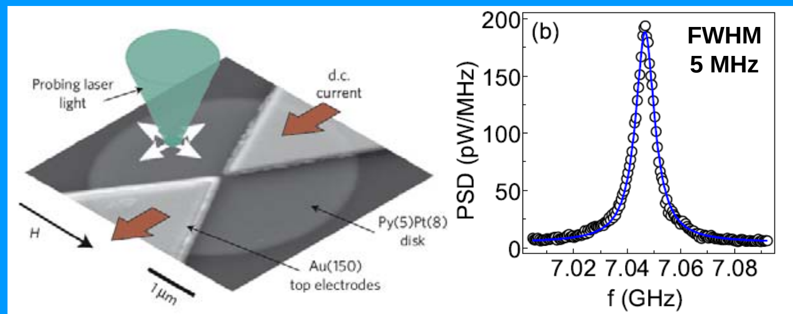
Control of parametric instability



Control of magnetic fluctuations



Excitation of coherent dynamics



…by pure spin current

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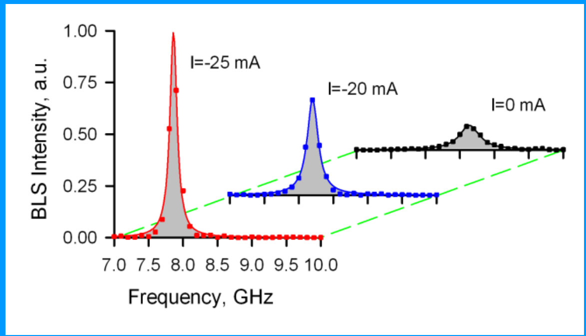
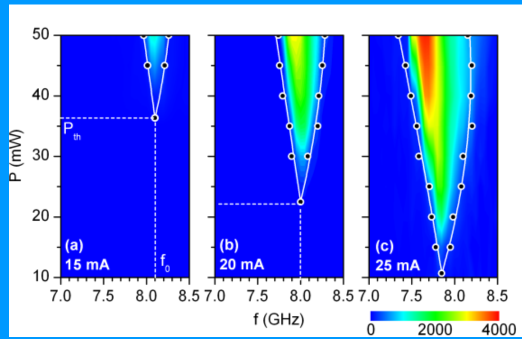
Outline

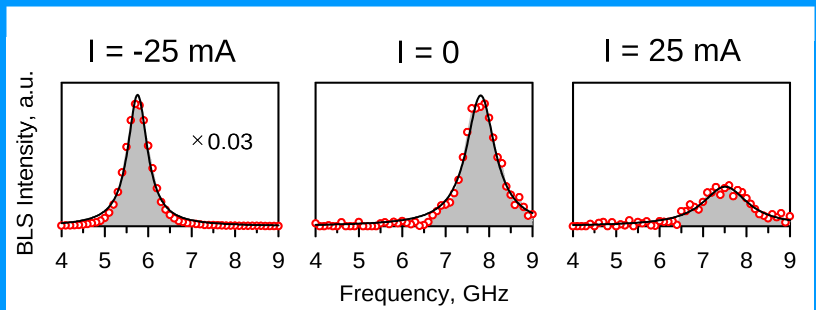
Control of effective FMR linewidth



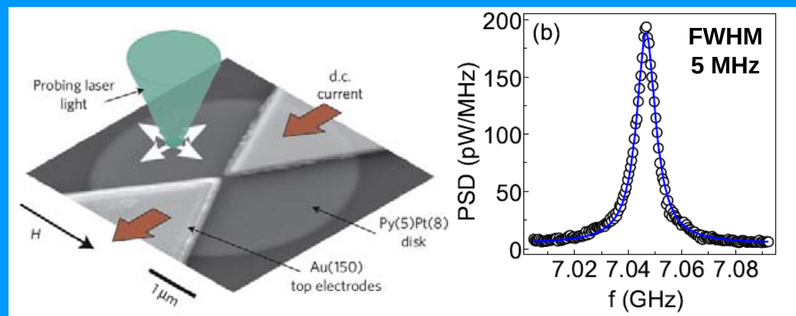
Control of parametric instability



Control of magnetic fluctuations



Excitation of coherent dynamics



…by pure spin current

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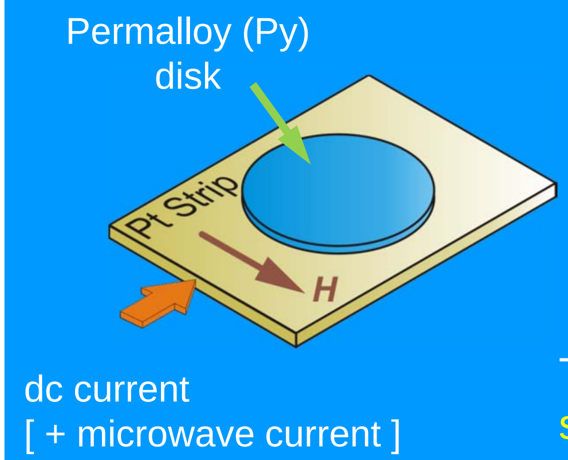
Test devices

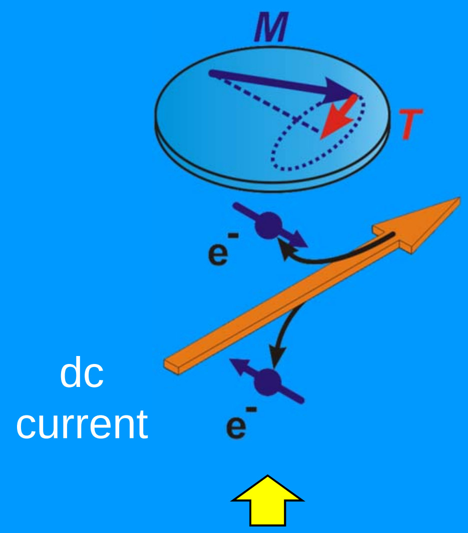


Disk: Permalloy (Py), ∅2 μm, 5 nm thick

Microstrip: Pt, 2.5 μm wide, 10 nm thick

dc current is applied through the Pt strip.

The operation of the device relies on the spin Hall effect (SHE) induced by electrical current in the Pt strip.



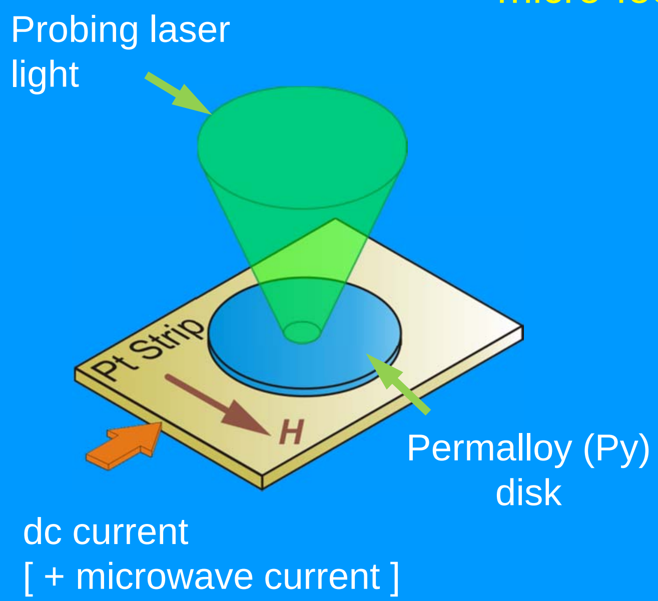
SHE produces a spin current at the interface with the Py dot, exerting spin transfer torque (STT) on its magnetization.

Depending on the direction of the current, spin current either stabilizes or destabilizes the magnetization.

SHE originates from spin-orbit scattering resulting in a deflection of conduction electrons with opposite spin orientations in opposite directions.

Measurement technique

To detect the magnetization dynamics we use
micro-focus Brillouin Light Scattering (BLS) spectroscopy.



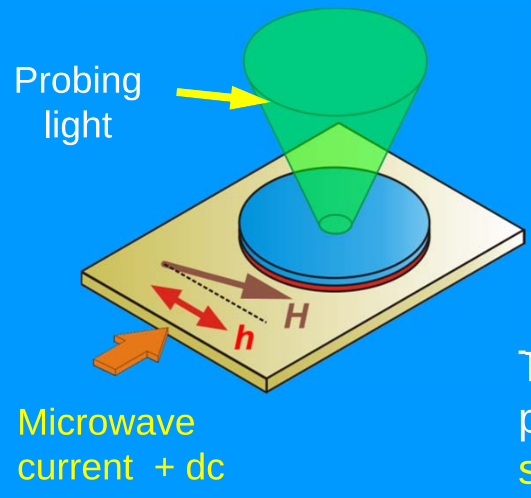
1. Probing laser light is focused onto the surface of the magnetic film into a diffraction-limited spot.
2. Light scattered from magnetic excitations is analyzed.

BLS signal is proportional to the
square of the dynamic magnetization
at the position of the probing light spot.

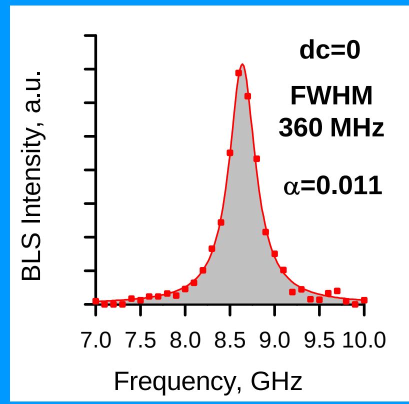
Available resolutions:

1. Frequency resolution 0.05-1000 GHz
2. Temporal resolution < 400 ps
3. Spatial resolution < 250/50 nm
4. Wavevector resolution < 10^6 cm^{-1}
5. Phase resolution

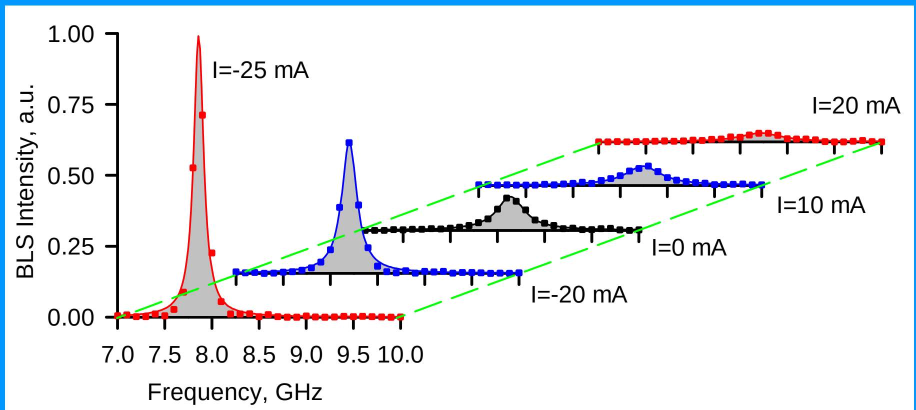
Control of effective damping in FMR



The FMR curve recorded without the dc current shows a linewidth of 360 MHz at *H*=900 Oe.



This corresponds to Gilbert damping parameter α=0.011, which is close to the standard value α=0.008 for Permalloy.



Effect of the current

Positive current: broadening of the FMR peak and reduction of its amplitude.

Negative current: increase of the amplitude and narrowing of the peak.

The smallest achieved α=0.004 is by a factor of 2 smaller than the standard value for Permalloy.

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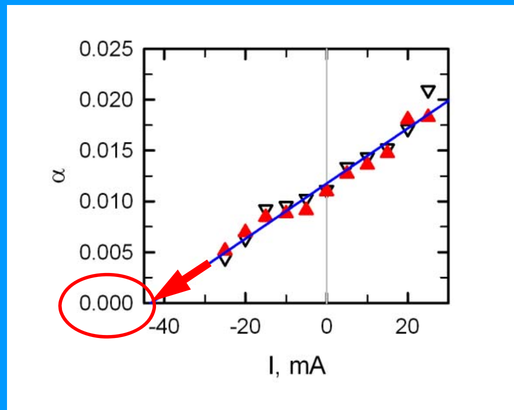
Appl. Phys. Lett. **99**, 172501 (2011).

Our ultimate goal:

To compensate completely the dynamic damping and to achieve excitation of coherent magnetization dynamics by spin current without application of microwaves



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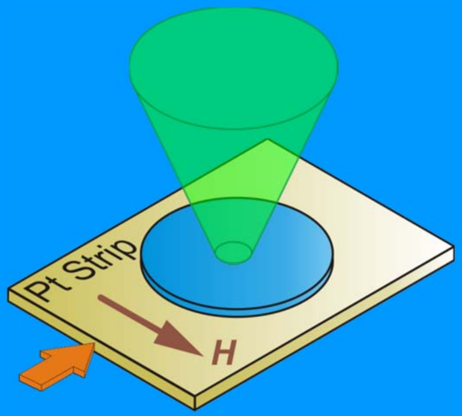
Control of magnetic fluctuations

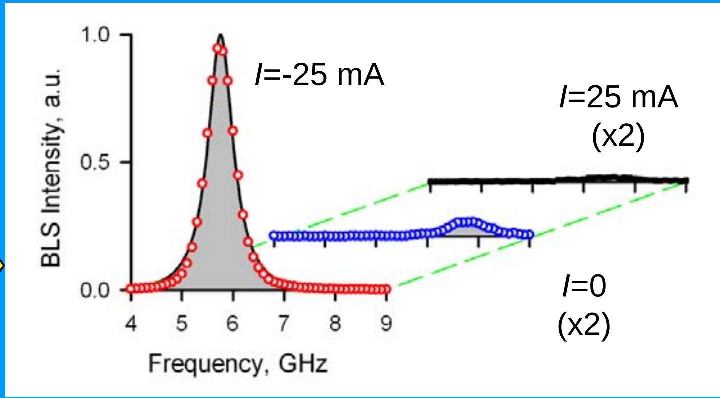


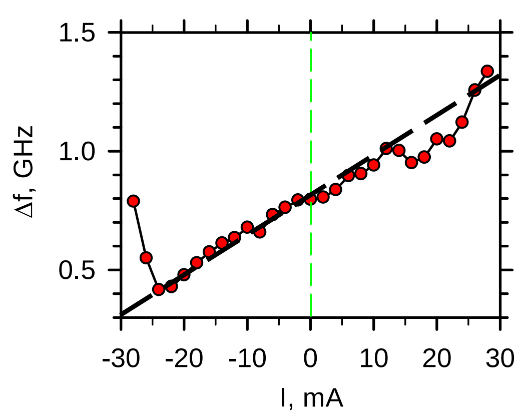
dc current
~~+ microwave current~~

Thermally-excited unifrom fluctuations are detected by BLS.

BLS spectra exhibit a peak with a Lorentzian shape.

The amplitude of the peak decreases at *I*>0 and increases at *I*<0.





The linewidth varies linearly with current at small *I*.

These behaviors are typical for modification of the effective damping by STT.

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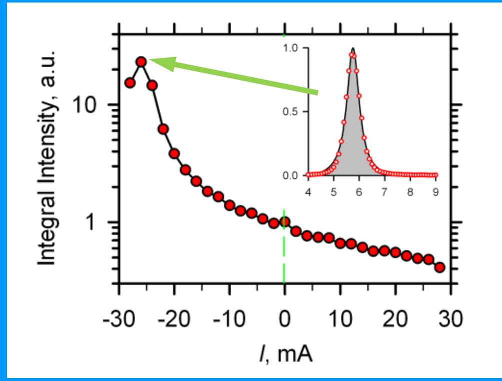
Phys. Rev. Lett. **107**, 107204 (2011).

NLD

Control of magnetic fluctuations

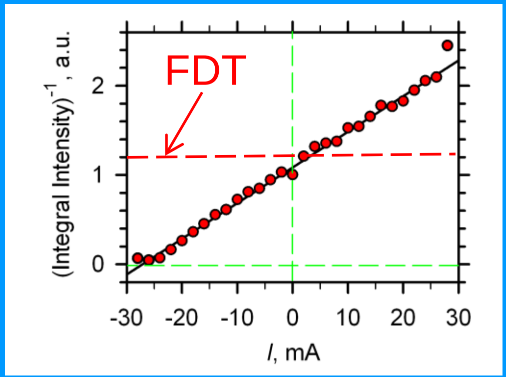
The integral under the measured peak is proportional to the average fluctuation energy in the mode.



At I=-28 mA, the integral intensity increases by more than a factor of 30, and at I=28 mA it decreases by more than a factor of 2.

Besides modifying the damping, STT changes the energy of magnetic fluctuations.

This phenomenon can be used for effective "cooling" of a magnetic system and provides practical ways for reduction of thermal noise in magnetic nano-devices.



In agreement with the non-equilibrium theory, the inverse integral intensity shows linear dependence on the current.

At $I=I_c$=-28 mA the integral intensity is expected to diverge (onset of auto-oscillations).

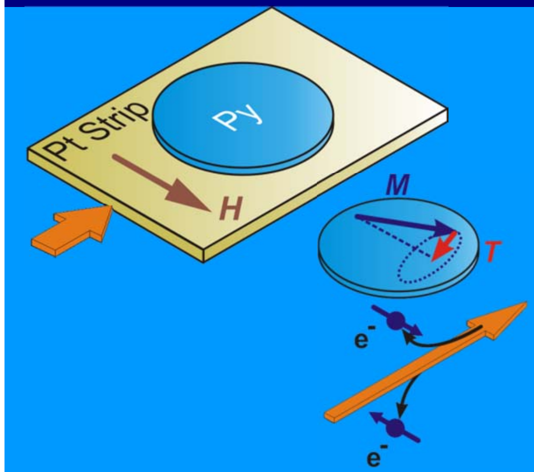
Instead, it saturates and starts to decrease at I<-26 mA.

Time-resolved measurements

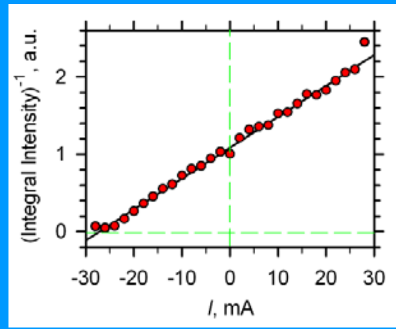
Close to the auto-oscillation onset, the flow of energy into the uniform mode saturates, whereas short-wavelength modes are further enhanced.

Phys. Rev. Lett. **107**, 107204 (2011).

STT vs Pt-thickness

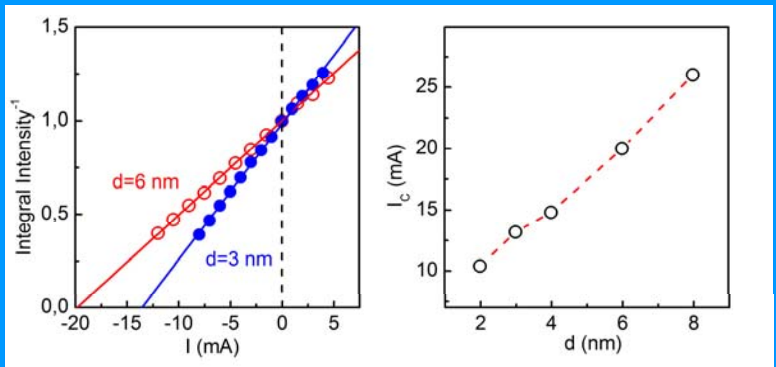


Devices with 10 nm thick Pt $\Rightarrow$ critical current $\approx$ 28 mA.



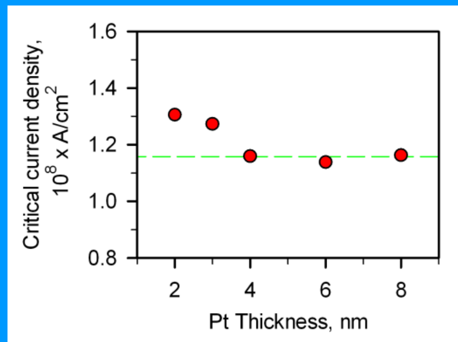
The most straightforward way to reduce necessary driving currents is the reduction of the Pt thickness.

(limited by the spin diffusion caused by the spin accumulation at the free Pt interface)



Reduction of the Pt thickness down to 2 nm results in monotonous decrease of the critical current.

Critical current density only slightly increases at small Pt thicknesses due to the finite spin-diffusion length.



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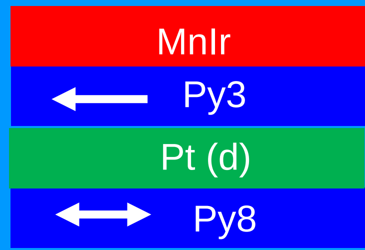
Appl. Phys. Lett. **102**, 132402 (2013)

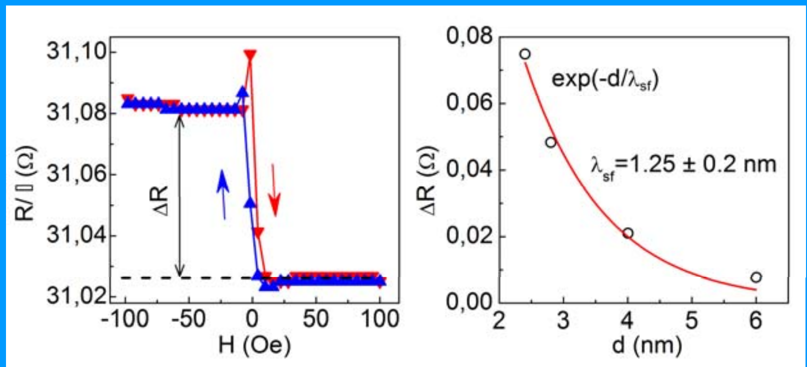
Spin diffusion length in Pt (Pt/Py!)

Literature data for spin diffusion length in Pt :
1.2-1.4 nm (Almaden, Cornell), 7 nm (Tohoku),14 nm (MSU)

Do we have the proximity effect in Py/Pt?

Another way to determine the spin diffusion length is to measure GMR.
Spin-valve stack tack: Py8/Pt(d)/Py3/$Mn_{80}Ir_{20}$/Ta1.5





GMR depends exponentially on the Pt thickness.

Due to the proximity effect of Py the spin-diffusion length is reduced and effectiveness of spin-current injection in Py/Pt system is enhanced

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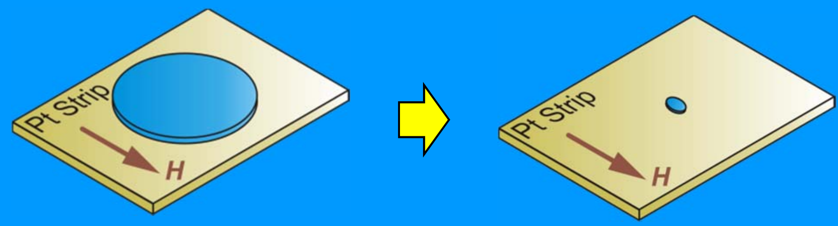
Appl. Phys. Lett. **102**, 132402 (2013);

How this limitation can be removed?

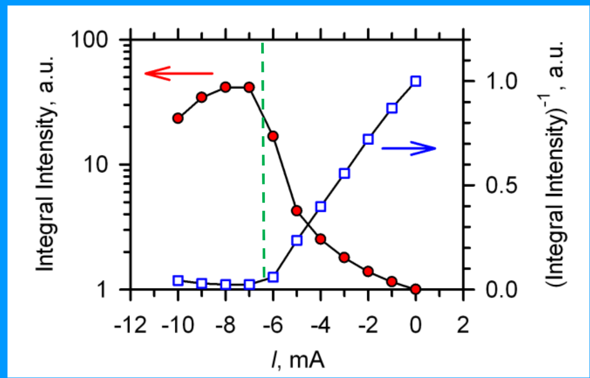
For example, one can try to reduce the sizes of the Permalloy element to make the mode spectrum strongly discrete.

Disk ∅2μm

Ellipse 100 by 50 nm



Results for Permalloy ellipses with dimensions of 100 by 50 nm:

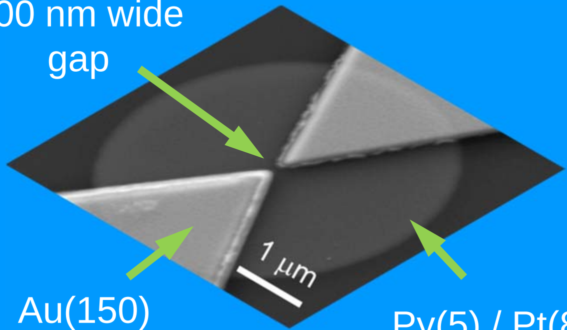


Very similar behaviors are observed.

Another solution: implementation of mode-selective enhancement.

Mode-selective amplification: local injection

100 nm wide gap

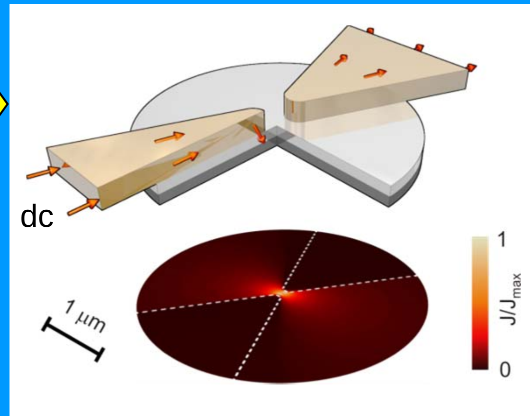


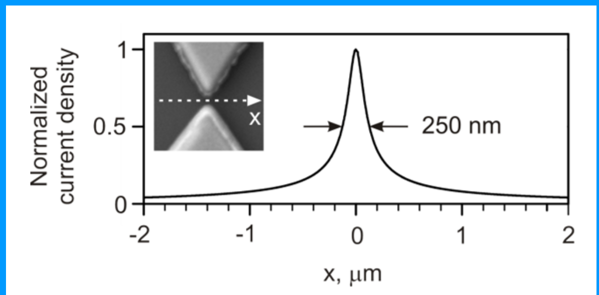
Au(150)
Top electrodes

Py(5) / Pt(8) disk
(∅ 4 µm)

SHE device with local injection of the spin current

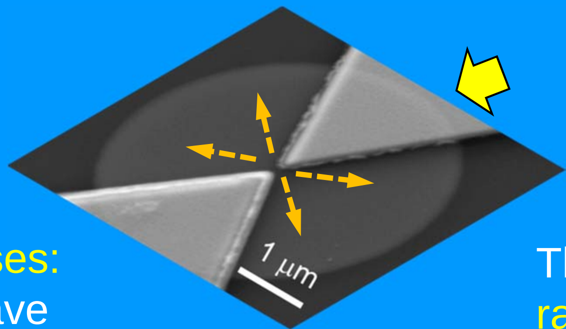
3D simulation of the current flow: the electrical current is strongly localized in the gap.





Active device area has typical dimensions of about 250 nm.

Spin waves can leave the active device area.

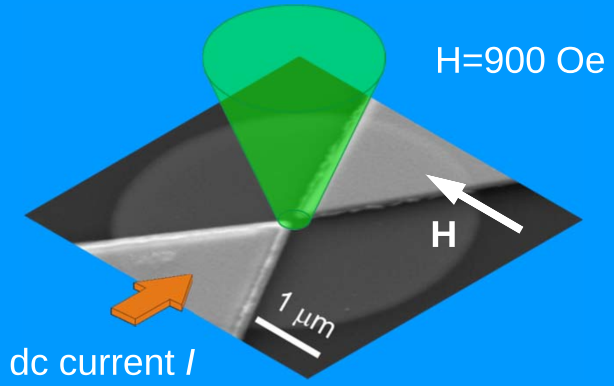


Frequency-dependent radiation losses: spin waves at higher frequencies have larger group velocities.
(cf.: talk yesterday, Kaiserslautern)

The mode with the smallest radiation losses should be predominantly enhanced by the spin current.

Nature Mater. **11**, 1028 (2012).

Auto-oscillations due to spin current

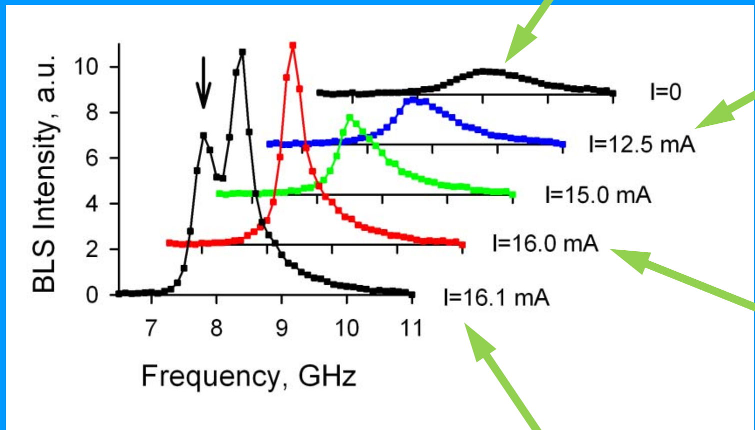


Probing spot is positioned in the gap.

Spectral BLS intensity is measured for different *I*.

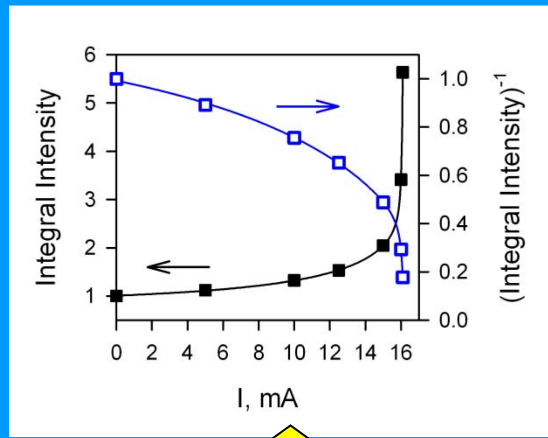
Before the onset of auto-oscillations

Spectrum of thermal magnetic fluctuations.



With increasing *I* the fluctuations are enhanced.

Low-frequency modes are enhanced stronger (frequency-dependent radiation losses).



The intensity of fluctuations diverges as the current approaches a critical value $I_c \approx 16.1$ mA (no saturation).

At $I=I_c$, a new peak appears in the BLS spectrum.

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Nature Mater. **11**, 1028 (2012).

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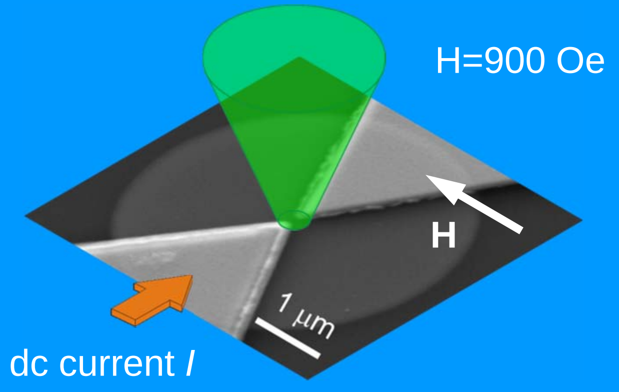
Auto-oscillations due to spin current



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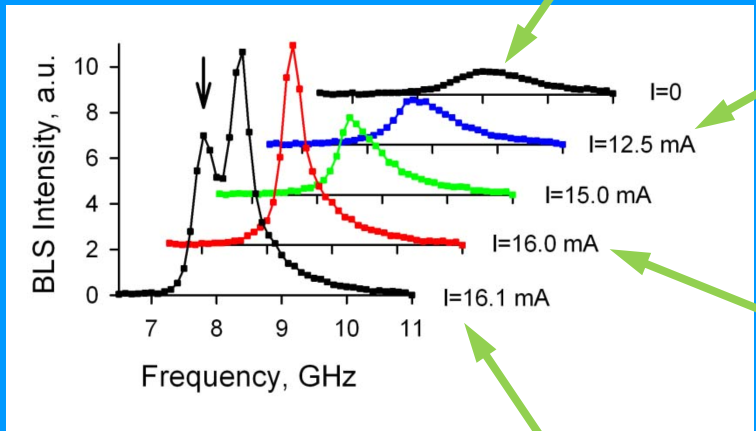

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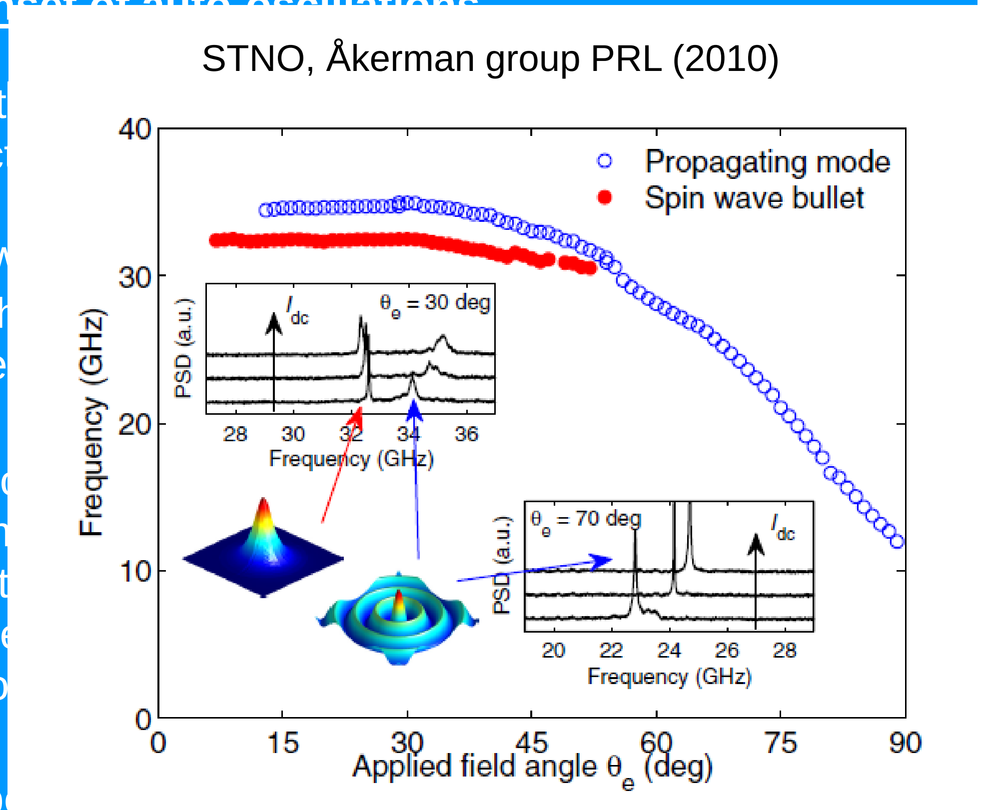

At $I=I_c$, a new peak appears in the BLS sp

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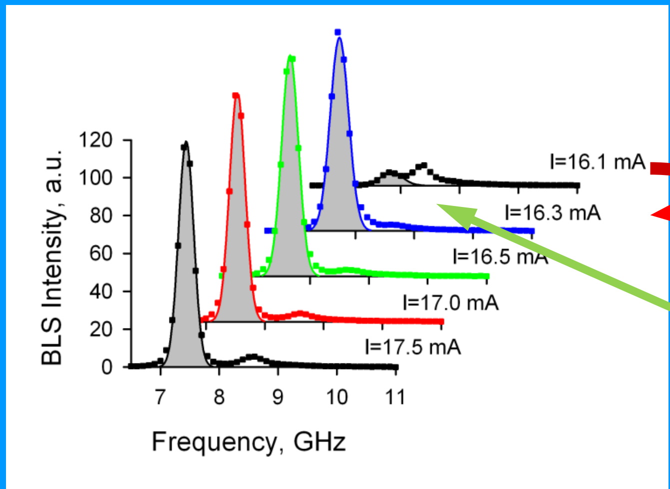
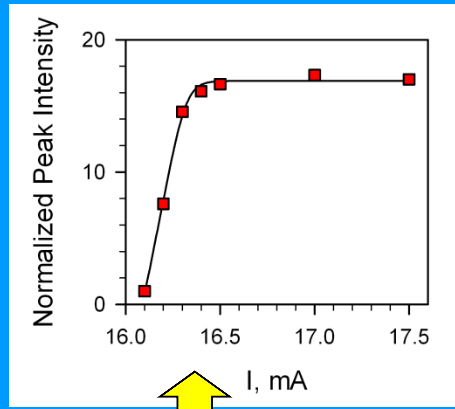
Spin-Hall nano-oscillator

After the onset of auto-oscillations



Increase of *I* by 1.3% results in dramatic increase of the intensity of the new peak – onset of auto-oscillations

Onset of auto-oscillations is accompanied by a decrease in the intensity of thermal fluctuations.

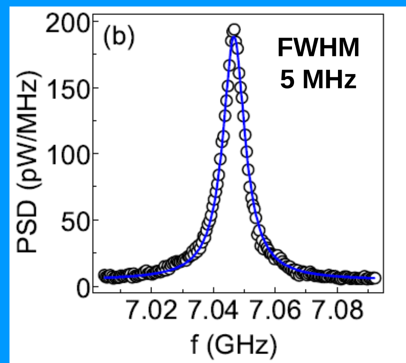


The peak rapidly grows and then saturates above 16.3 mA.

Electronic measurements with similar devices, PRL **110** 147601 (2013):

Microwave emission by a spin Hall nano-oscillator

R. H. Liu, W. L. Lim, and S. Urazhdin
Department of Physics, Emory University, Atlanta, GA 30322



Oscillation Linewidth is 5 MHz at 7 GHz (T=50 K)
– proof of high coherence degree

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Nature Mater. **11**, 1028 (2012).

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Comparison with Cornell's results

PRL 109, 186602 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Magnetic Oscillations Driven by the Spin Hall Effect in 3-Terminal Magnetic Tunnel Junction Devices

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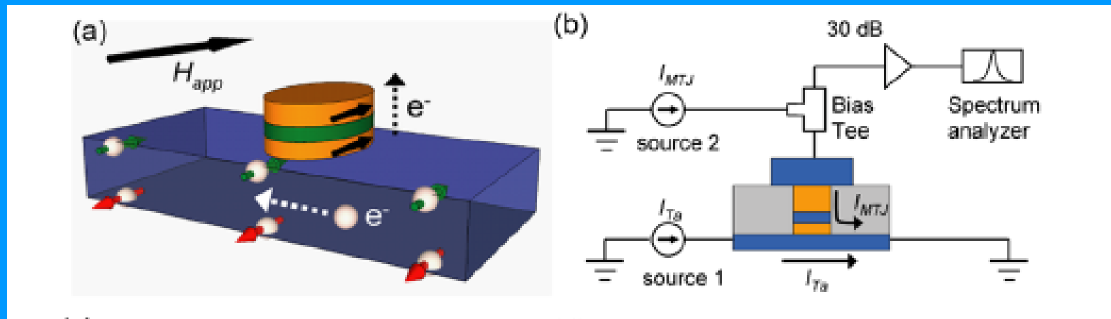
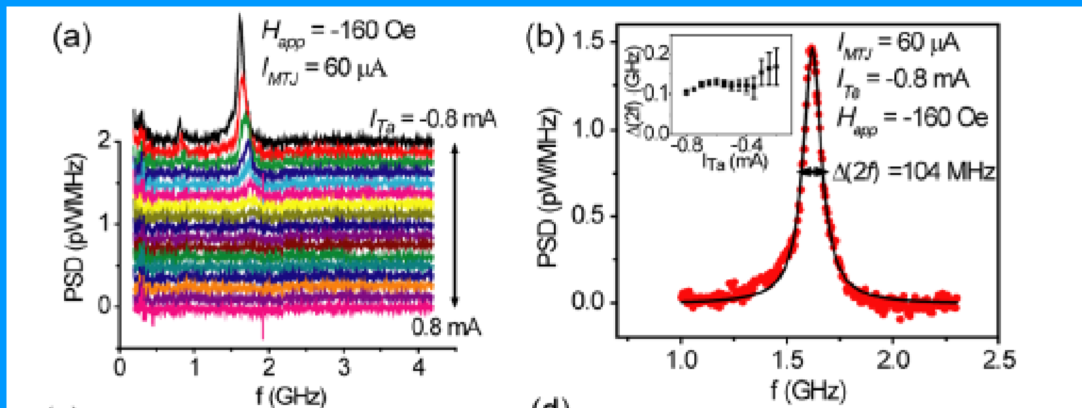
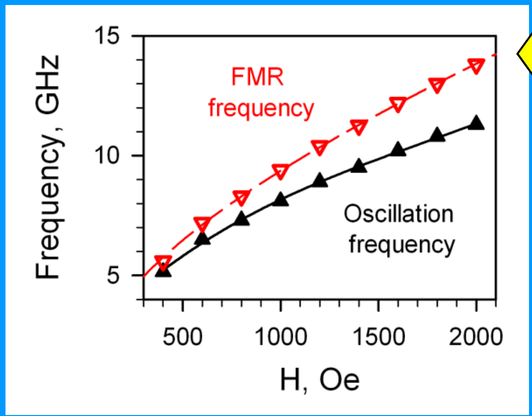
(Received 3 July 2012; published 31 October 2012)





Properties of SHNO

Tunability of oscillations

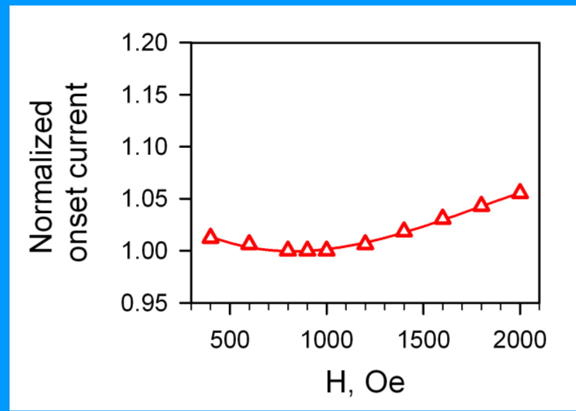


Stable transition to the auto-oscillation regime was observed over a wide range of static fields H=400-2000 Oe.

Onset current varies by only 5% within this range of H.

Onset current shows a minimum at H=900 Oe.

Minimum I_c=16. 1 mA corresponds to $J=3\times10^8$ A/cm^2



Auto-oscillation frequency is situated below the frequency of the uniform ferromagnetic resonance (FMR) in the Permalloy film and below the lowest frequency in the spin-wave spectrum.

The shift of the auto-oscillation frequency with respect to FMR increases with increasing H.

The auto-oscillation mode does not belong to the normal modes of the system and appears spontaneously at the onset current.

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Nature Mater. **11**, 1028 (2012).

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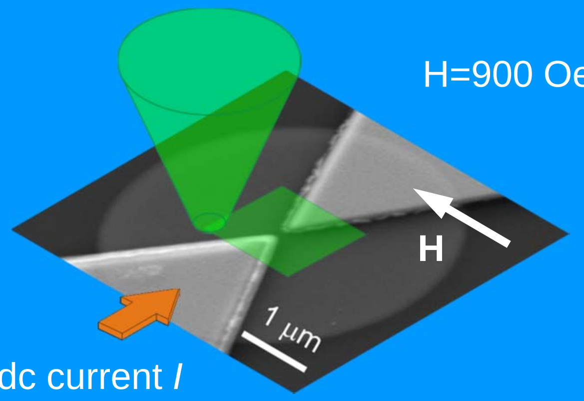
Self-localization of the oscillations



Auto-oscillation mode

To characterize the auto-oscillation mode, we performed two-dimensional mapping of the dynamic magnetization at the frequency of auto-oscillations.

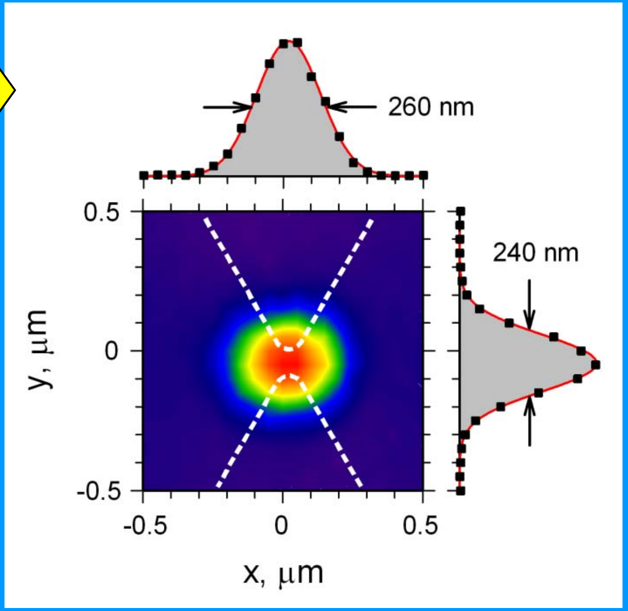
We rastered the probing laser spot in the two lateral directions and simultaneously recorded the BLS intensity.

Auto-oscillations are localized in a very small area in the gap between the electrodes.

The measured spatial distribution is a result of convolution with the instrumental function determined by the shape of the laser spot (∅≅250 nm).

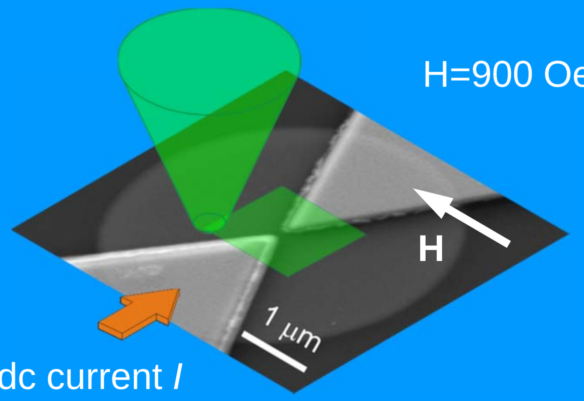
The real size of the auto-oscillation area is less than 100 nm, significantly smaller than the characteristic size of the current localization.

The auto-oscillation mode is the nonlinear self-localized spin-wave "bullet".



Nature Mater. **11**, 1028 (2012).

Self-localization of the oscillations

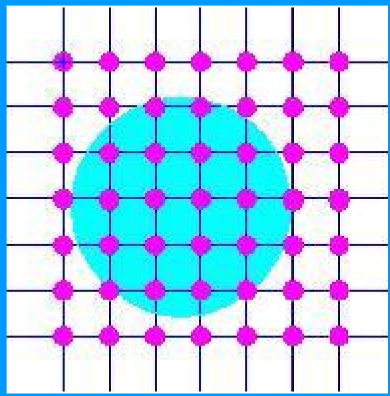


Auto-oscillation mode

To characterize the auto-oscillation mode, we performed two-dimensional mapping of the dynamic magnetization at the frequency of auto-oscillations.

We rastered the probing laser spot in the two lateral directions and simultaneously recorded the BLS intensity.

Auto-oscillations are localized in a very small area in the gap between the electrodes.



The measured spatial distribution is a result of convolution with the instrumental function determined by the shape of the laser spot (∅≅250 nm).

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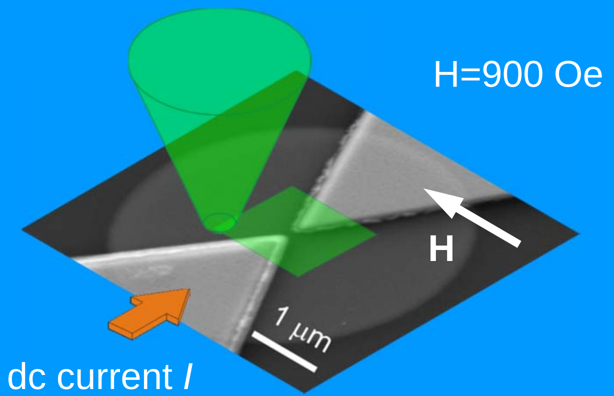

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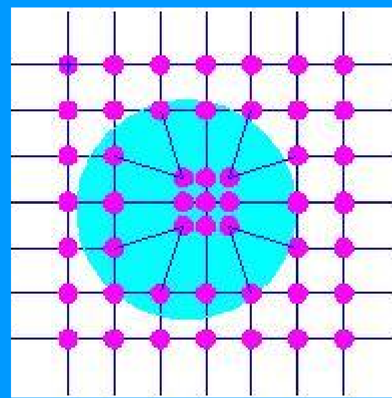

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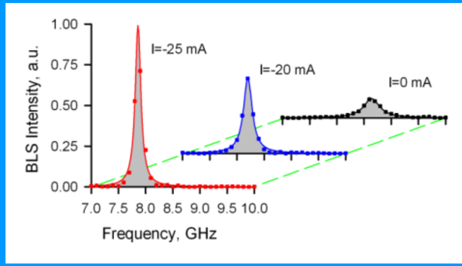
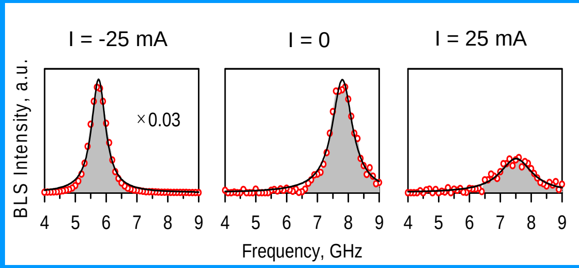
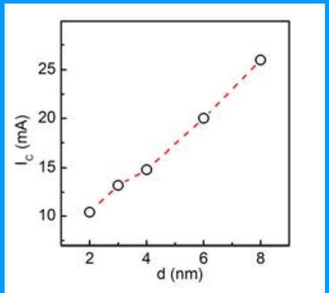
Conclusions

Using pure spin currents one can achieve significant variation of the effective damping in FMR and parametric pumping experimetns.

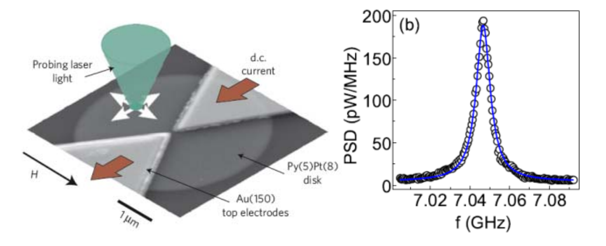




Pure spin currents can also be used to enhance or suppress high-frequency magnetic fluctuations.



Due to the proximity effect of Py the spin-diffusion length is reduced and effectiveness of spin-current injection in Py/Pt system is enhanced



Coherent auto-oscillations due to the pure spin current are achieved by using the mechanism of mode-selective enhancement in devices with local current injection.

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SEVENTH FRAMEWORK PROGRAMME

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NLMD